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Characterizing the exceptional 2014 drought event in São Paulo by drought period length

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Abstract In the last decade, the southeast region of Brazil has been suffering severe water shortages. Here, we propose to compute the expected drought period length to characterize the drought events in the region of São Paulo. We report the unique properties of the exceptional drought event during the austral summer 2014 by showing the differences and similarities to the very dry season in 2001 and the mild dry seasons in 2006 and 2015. Furthermore, we investigate the correlations of the abnormal precipitation deficit with the ocean and atmospheric patterns. In comparison to other drought events, we validate the hypothetical mechanism that underlies the exceptional drought 2014: (1) The existence of an anomalous high pressure center in the area acts as a blocking mechanism that prevents moisture transport from the Amazon and passage of cold front systems from south Brazil. This blocking high has been observed in all dry seasons considered, with much larger magnitude in 2014. (2) The much faster increasing trend of the anomalous sea surface temperature acts as a strong feedback which intensified the extreme climate conditions. The unprecedented increasing trend of the SST in 2014 was not observed in other climate variables representing a high pressure center. Therefore, we conclude that the exceptional drought 2014 was enhanced by the feedback mechanism of anomalous warming of SST in the South Atlantic Oceans, which was resulted from the anomalous high pressure.

Keywords Drought period length · Precipitation · Southeast Brazil · Sea surface temperature · Sea level pressure · South Atlantic ocean

1 Introduction

Water availability is crucial for the São Paulo area since this region is the most populated area in Brazil and around 61% of Brazil's electricity is currently produced by hydropower plants according to the Brazilian Electricity Regulatory Agency (http://www2.aneel.gov.br/aplicacoes/capacidadebrasil/OperacaoCapacidadeBrasil.cfm). Drought events caused a number of impacts on water availability for consumption, agricultural irrigation and hydropower production. As it has been reported in the literature (Coelho et al. 2016b), starting from 1998 till the early 2015, the southeast region of Brazil was predominated by a precipitation deficit in the austral summers. The entire austral summer of 2014 experienced the largest negative precipitation anomaly of −249.7 mm with respect to the 1981–2010 climatological mean value for the southeast Brazil region (574.3 mm) (Coelho et al. 2016a, b). Due to the deficit rainy season accompanied by record high temperatures and subsequent increase in water demand by the large population in this region, the largest reservoir system Cantareira reached the unprecedented lowest levels in early 2015 since 1951 (Nobre

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et al. 2016). The local government was forced to install a pumping system that was able to extract water from deep reservoir levels that were never reachable in the past. It was documented in (Cavalcanti and Kouksy 2001; Drumond and Ambrizzi 2005; Dufek and Ambrizzi 2008) that, in 2001, the region of São Paulo also experienced an unprecedented precipitation deficit leading to an energy crisis due to water shortage. Based on the standardized precipitation index, the 2014 summer drought event was classified as exceptionally dry (Coelho et al. 2016a). However, the 2015 drought was only classified as very dry event, being much less severe than 2014. In addition, the austral summer drought in 2001 was the second driest year with negative precipitation anomalies after 2014. In comparison to 2001 and 2014, the other dry years like 2006 and 2015 can be regarded as normal drought conditions with less impacts to this region.

The factor resulting in drought events in normal years is the mechanism of high pressure in the region of São Paulo, which blocks the arrival of cold fronts from the south. The South Atlantic Convergence Zone (SACZ) plays a crucial role in normal years without drought events (Herdies et al. 2002). The SACZ is a northwest-southeast oriented band of clouds that extends from the Amazon to the southwestern South Atlantic, passing over the southeast region of Brazil. This diagonal band of convective clouds configures the diagonal precipitation patterns in the region of São Paulo and even more widely the entire region of southeast Brazil. This convection is associated with tropical humidity convection from the Amazon region towards the southeast direction via the so-called low level jet. The location of SACZ oscillates meridionaly. Extreme rainfall events in the Southeast Brazilian region occur when the SACZ is strong, since it brings moisture from the Amazon. On the other hand, during the austral summers in 2014 and 2015, very few observations of SACZ cases were reported and hence the low level jet was displaced westward and the moisture transport over the SACZ region was interrupted. In consequence, the precipitation deficit appeared in the region of São Paulo. The reason of the absence of SACZ cases was considered to be caused by an anomalous high pressure system which blocked moisture flow from the Amazon and passage of cold front systems from south Brazil (Marengo et al. 2015; Coelho et al. 2016a).

However, in the extreme drought event in 2014, this blocking mechanism of high pressure in the São Paulo region was even more elaborated and not so far completely understood. Besides this high pressure issue, it is also known that there was also an anomalous warming of sea surface temperature in the south Atlantic ocean nearby the Southeast Brazilian region. Coelho et al. (2016b) proposed some schematic frameworks for possible mechanisms of the drought event 2014, which need further evidence to understand the causes of droughts. The uniqueness of the 2014 summer drought calls for novel methodologies to tackle the underlying complex interacting patterns as well.

Recently, we proposed a new measure based on the expected drought period length to understand the recent drought events in the Amazon regions (Zou et al. 2016). In this work, we will further demonstrate the applicability of this method to disclose the particular characteristics of the extreme drought event in 2014 in São Paulo. Different from the literature, we achieve this goal by a detailed comparative study of the recent four extreme drought events. Note that the previous study focused on the particular drought event in 2014 only (Coelho et al. 2016b) or the most recent two consecutive events in 2014 and 2015 (Seth et al. 2015). More specifically, we study the climate conditions in 2014 (exceptional dry year), by comparing the difference and similarities to 2001 (very dry year), 2006 and 2015 (mild dry years), which hence provide unique insights into the 2014 drought event in historical context.

To this end, we investigate the atmospheric and oceanic conditions that are able to generate the observed precipitation variabilities during several major summer drought events in the São Paulo region of Brazil. In particular, we show the relationship of the precipitation deficit with high pressure blocking system which is represented by sea level pressure, specific humidity, and 500 hPa geopotential hight (Luiz Silva et al. 2015). Furthermore, we study the influence of the sea surface temperature in the Atlantic Ocean region close to the coast of Brazil, which is generally considered as one key parameter for understanding drought conditions (Pampuch et al. 2016).

2 Data

We follow the literature (Rao et al. 2016) and make use of Climate Prediction Center (CPC) gauge based analysis of global daily precipitation (http://ftp.cpc.ncep.noaa.gov/precip/CPC_UNI_PRCP/GAUGE_GLB/V1.0/) for a period of 26 years from 1979 to 2005 and 2006 to 2015 (http://ftp.cpc.ncep.noaa.gov/precip/CPC_UNI_PRCP/GAUGE_GLB/RT/) with 0.5° latitude 0.5° longitude horizontal resolution. In CPC a suite of unified precipitation products are created with consistent quality improvement, which are done by combining all sources of information available at CPC, by taking advantage of the optimal interpolation and objective analysis techniques (Rao et al. 2016).

From the NCEP-NCAR Reanalysis I product (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surface.html), we obtain the following data sets for a period from 1948 to 2015: (1) the sea level pressure (SLP) with 2.5° latitude × 2.5° longitude horizontal resolution, (2) specific humidity (SHUM) at 925 hPa level, and (3) geopotential height (GPH) at 500 hPa level. The sea surface temperature

(SST) is evaluated using NOAA of 0.25° latitude × 0.25° longitude high resolution data products (Reynolds et al. 2007) (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.highres.html).

Time series for precipitation (PREC), SLP, SHUM, and GPH of daily temporal resolution were built for the metropolitan region of São Paulo chosen as $47.75°W–45.25°W$, $24.75°S–22.25°S$. The region of interest for the south Atlantic ocean is chosen as $35°W–22°W$, $50°S–32°S$. Furthermore, daily precipitation anomaly series are calculated relative to a base period of 1979–2005. For SLP, SHUM, and GPH, daily anomaly series are computed relative to a base period of 1948–2005. Following the previous study by Coelho et al. (2016a), the months from December to March represent the peak of the wet season in southeast Brazil, which is therefore defined as the extended austral summer period.

3 Methods

Recently, we have proposed to compute the expected Drought Period Length (DPL) to quantify the dry conditions in the Amazon region (Zou et al. 2016). In this work, we further show the applicability of this new measure by studying the extreme events in the precipitation patterns in the area of São Paulo (southeast Brazil). More specifically, given the daily precipitation anomaly series $PREC(t)$ in the austral summer period (shown in Fig. 1a), we compute the expected drought period length $DPL(t)$ that characterizes the waiting time from a given day to the next first non-negative rainfall anomaly as follows:

$$DPL(t) = \min\{\tau : PREC(t+\tau) \geq 0, \tau \in [0, \infty)\}. \quad (1)$$

The $DPL(t)$ captures the expecting time when anomaly series goes from negative to positive, characterizing the expectation to have an excess rain anomaly.

Note that $DPL(t)$ is different from computing the time length of each drought event which needs a proper definition of an event. For instance, we first define the arrival time of a dry event if DPL is larger than a proper threshold. The next step is to disclose the properties of the arrival times between two events and their distribution. Another method is to focus on the properties of the length of each event. Nevertheless, both methods provide alternative ways to characterize the underlying processes (Zou et al. 2014).

In this work, we take a slightly different approach. Since the average drought period length is about 5 days (as shown in Fig. 2), we define a drought event if DPL is greater than 2 weeks. We will discuss about the effects of such thresholds later and consistent results have been obtained. For the particular seasonal periods, the drought events are highlighted in Fig. 1b.

In the next step, we look back how SLP, SHUM, SST, GPH change during these particular time windows, meanwhile, their respective directions of changes between consecutive observations. Taking SLP as an example, we first obtain the differenced series by $\Delta SLP = SLP(t+1) - SLP(t)$. SLP is in an increasing phase if ΔSLP is positive, in contrast, SLP is in a decreasing phase if ΔSLP is negative. Hence, ΔSLP captures the

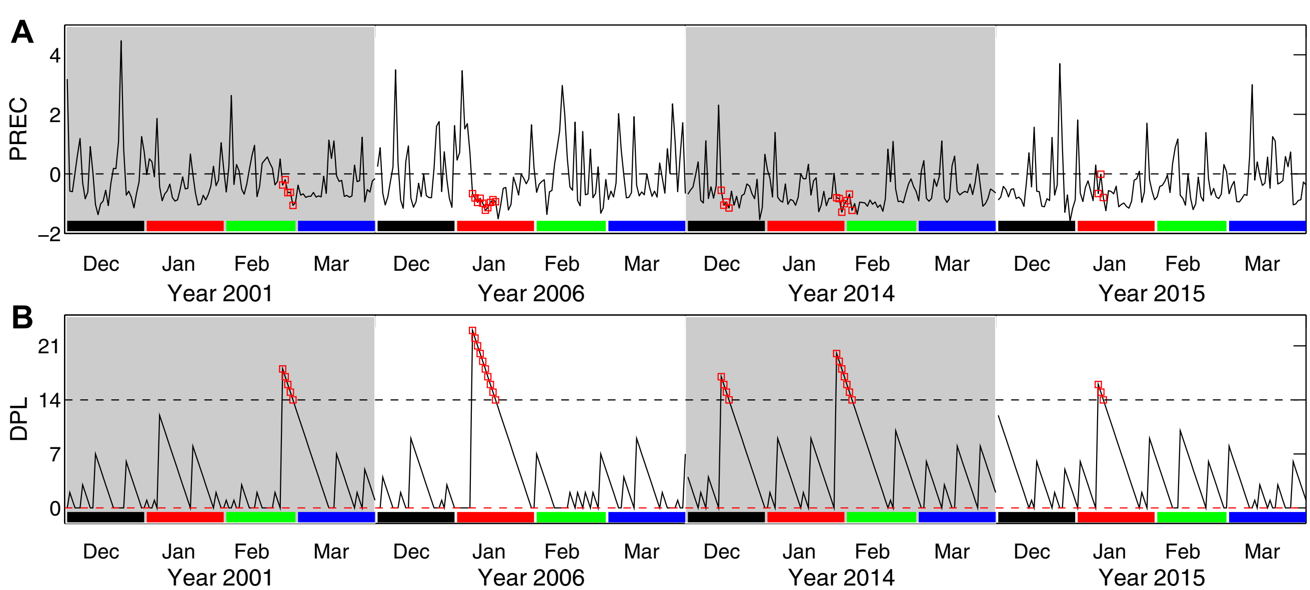

Fig. 1 **a** Precipitation anomalies in austral summers for the respective years. **b** Drought period length (DPL). Days when DPL are longer than 2 weeks are highlighted by red squares

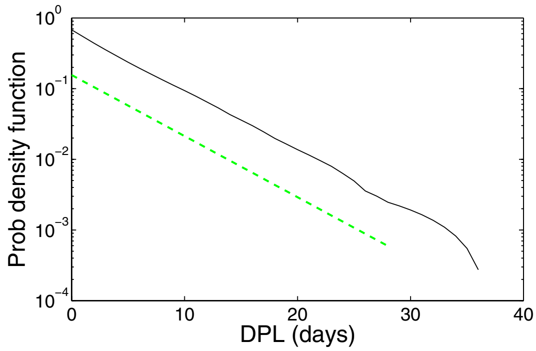

Fig. 2 Semi-logarithmic plot of the cumulative probability density function of *DPL* for the period 2006–2015, which follows an exponential law $\sim e^{-\lambda t}$. Estimate of $\lambda \approx 0.199$ is done by a linear regression in the scaling regimes, where the dashed line is the corresponding linear fitting and the significance is discussed in the main text

apparent increase (or decrease) trends in the sea level pressure over time window of a month M. In order to quantify changes in the *differenced* space, we define the ratio

$$r_D^M = \frac{\#\{\Delta\text{SLP} > 0\}}{\#\{\text{DPL} >= \text{threshold}\}}, \tag{2}$$

which captures the number of days that SLP are in the increasing phase in the month M provided DPL is larger than some threshold value. Since there are four months (December, January, February, and March) included in the analysis, we measure the strength of increasing phase as $r_D = \sum r_D^M/4$. We set $r_D^M = 0$ if no drought events are identified in month M. The same calculation in the differenced space is performed for ΔSHUM, ΔSST and ΔGPH.

Meanwhile, for the original time series of SLP, we compute

$$r_S^M = \frac{\#\{\text{SLP} > 0\}}{\#\{\text{DPL} >= \text{threshold}\}}, \tag{3}$$

which captures the period length of positive anomalies of SLP when DPL is larger than the threshold in the month M. The strength of positive anomalies during the whole austral summer is defined as $r_S = \sum r_S^M/4$. The same calculations are done for time series of SHUM, SST and GPH. Comparing to r_D, r_S discloses the properties in the *original* space since the original time series is used. Note that consistent results have been obtained when considering different threshold values.

A further note is that we use the denominator 4 when computing r_D and r_S. This captures the drought period length over all four months in the entire austral summer, reflecting the accumulation effects of the precipitation deficits.

4 Results

Let us start by showing the general behavior of the drought period length for the period 2006–2015 (including all summers and winters) in the region of São Paulo. Interestingly, we find that DPL of the precipitation process follows an exponential law, namely, $p(t) \sim e^{-\lambda t}$, as shown in Fig. 2. This exponential distribution suggests that generally the occurrence of drought period length of t does not affect the probability that a second event of length $t + 1$ will occur, meaning that dry period length occurs independently and, hence, it is a memoryless process. However, the extreme drought events of large DPL values do not follow this pattern because they are in the tail of the distribution showing large deviations from the hypothetical exponential distribution. Large deviations may come from the perturbations by other processes, which are the focus of this work.

In order to choose a proper threshold value to define an extreme drought event, we first study the average behavior of drought events in normal dry seasons with the help of the cumulative probability density function of DPL for the period 2006–2015. The characteristic exponent of this distribution is estimated as $\lambda \approx 0.199$ in the scaling regime as presented in Fig. 2. Regarding the goodness of fit of the exponential distribution, we have computed: (1) the sum of squares due to error is 5.2×10^{-5} which indicates that the exponential fit has a small random error component and it is useful for prediction; (2) the R-square value is 0.998 which indicates that 99.8% of the total variance is accounted for by the exponential fit; (3) the χ^2-test and $\chi^2 = 0.09$ suggests that the null hypothesis of an exponential law could be accepted at a significance level of 0.1.

We further check the hypothetical stochastic properties of DPL series by computing both the coefficient of variation C_v and the local variation of the inter-spike intervals L_v (Shinomoto et al. 2003). In particular, $C_v \approx 0.94$ indicates the hypothetical exponential model. However, the computation of L_v is more affected by zeros of the DPL series. When removing all zeros, $L_v \approx 0.85$. Therefore, both C_v and L_v are in favor of the hypothesis that the series of the drought period length is from a memoryless process.

In addition, the parameter $\lambda \approx 0.199$ represents that the mean drought period length is about $1/\lambda \approx 5$ (days), which provides insight for choosing a threshold value in defining an extreme drought event. More specifically, the extreme DPL values for the particular years 2001, 2006, 2014 and 2015 fall in the right tail of the distribution, and therefore their behavior might not be well described by the exponential model. With this motivation, we study how the SLP, SHUM, SST and GPH behave when the São Paulo area experienced drought conditions as captured by DPL longer than 2 weeks.

Figure 3 shows the correlations of DPL to the SLP. As defined by DPL, the severe drought event in 2001 appeared

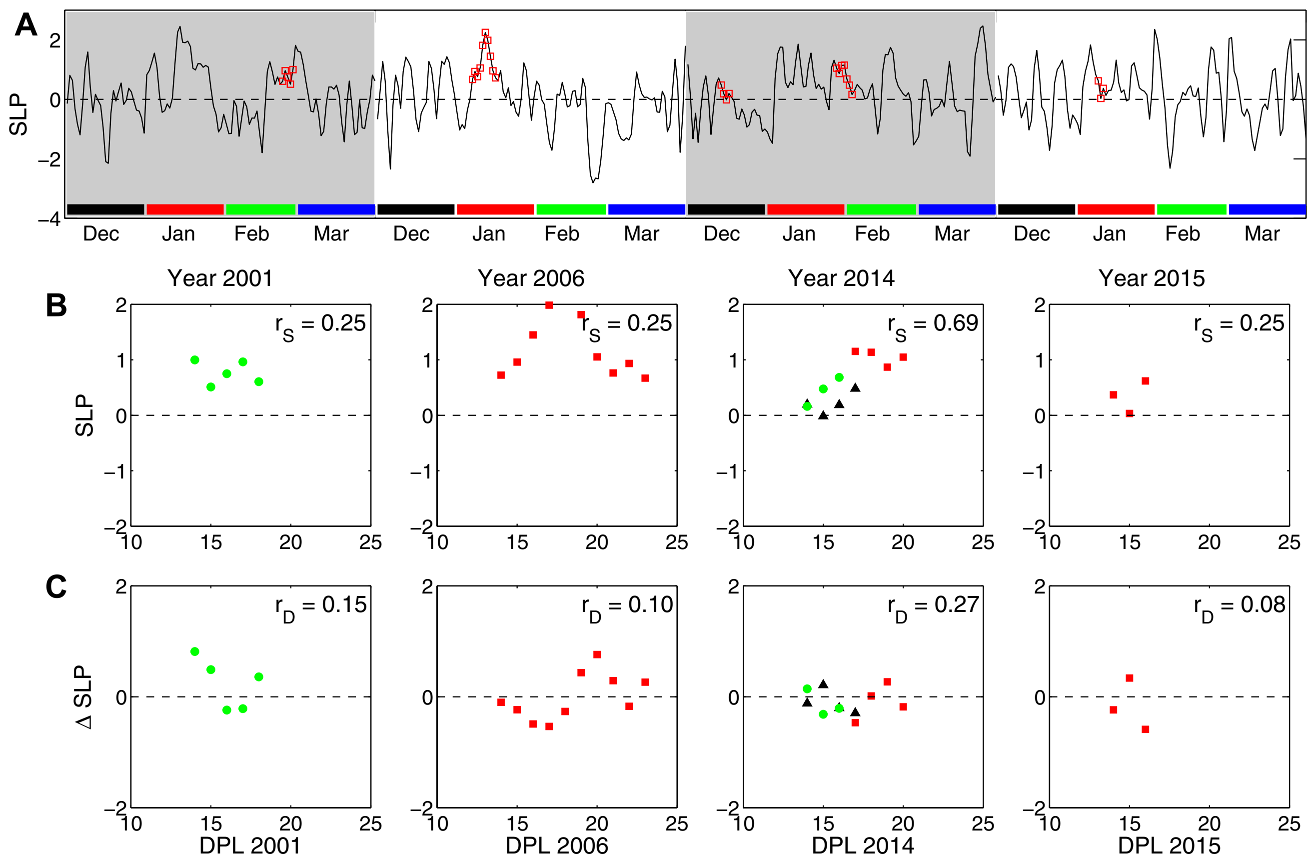

Fig. 3 **a** Seasonal time series of sea level pressure (SLP) with days that DPL are longer than 2 weeks are highlighted by red squares. **b** Scatter plot shows potential correlations between DPL and SLP. **c** Scatter plot shows potential correlations between DPL and Δ*SLP*. December (black filled triangle), January (red filled square), February (green filled circle)

mainly in the end of February which was highlighted in Fig. 3a. During this drought period, the SLP were significantly above zero. For the mild dry seasons in 2006 and 2015, the drought events appeared in January, when positive SLP anomalies were observed. For the exceptional dry year 2014, the dry events appeared in December, January and February, when positive SLP anomalies were observed as well. However, this period spanned for three months and the strength of positive anomalies as observed are captured by the measure of $r_S = 0.69$. In contrast, the limited temporal scales of 2001, 2006, and 2015 yielded the small value of $r_S = 0.25$.

In the differenced space, we do *not* find obvious evidence that the SLP shows trends up or down for all years as indicated by small values of r_D in Fig. 3b.

Figure 4 shows the correlations of DPL to the SHUM. First, let us discuss the results in the original space (Fig. 4b). In the very dry year 2001, positive SHUM anomalies were observed in February, which yielded $r_S = 0.2$. In the exceptional dry year 2014, however, we find mainly negative SHUM values in December, January and February with $r_S = 0.08$. In the mild dry years of 2006 and 2015, we get negative SHUM values in January with small values of $r_S = 0.0$. Second, in the differenced space (Fig. 4c), SHUM showed a weak increasing trend of $r_D = 0.15$ in February 2001. In the exceptional year 2014, the increasing trend was strengthened to $r_D = 0.42$. However, in the mild dry years of 2006 and 2015, no significant changes have been found, since r_D varied around zero in January. In conclusion, we do not observe pronounced correlations of DPL to the SHUM.

Figure 5 shows the potential correlation of DPL to the SST. In the original space (Fig. 5b), in the very dry days in 2001, positive SST anomalies were observed in February only which resulted in $r_S = 0.25$. However, in the exceptional dry season in 2014, a much longer time interval of positive SST values is found, spanning from December to February, which resulted in $r_S = 0.56$. In contrast, in the mild dry days in 2006 and 2015, positive SST values only appear in January, leading to $r_S = 0.25$. A pronounced difference has been found in the differenced space (Fig. 5c). More specifically, in the very dry summer in 2001, the SST mainly experienced a decreasing phase as captured by a much smaller value of $r_D = 0.1$. In 2014, however, there was a significant increasing trend in the SST from December to the early February,

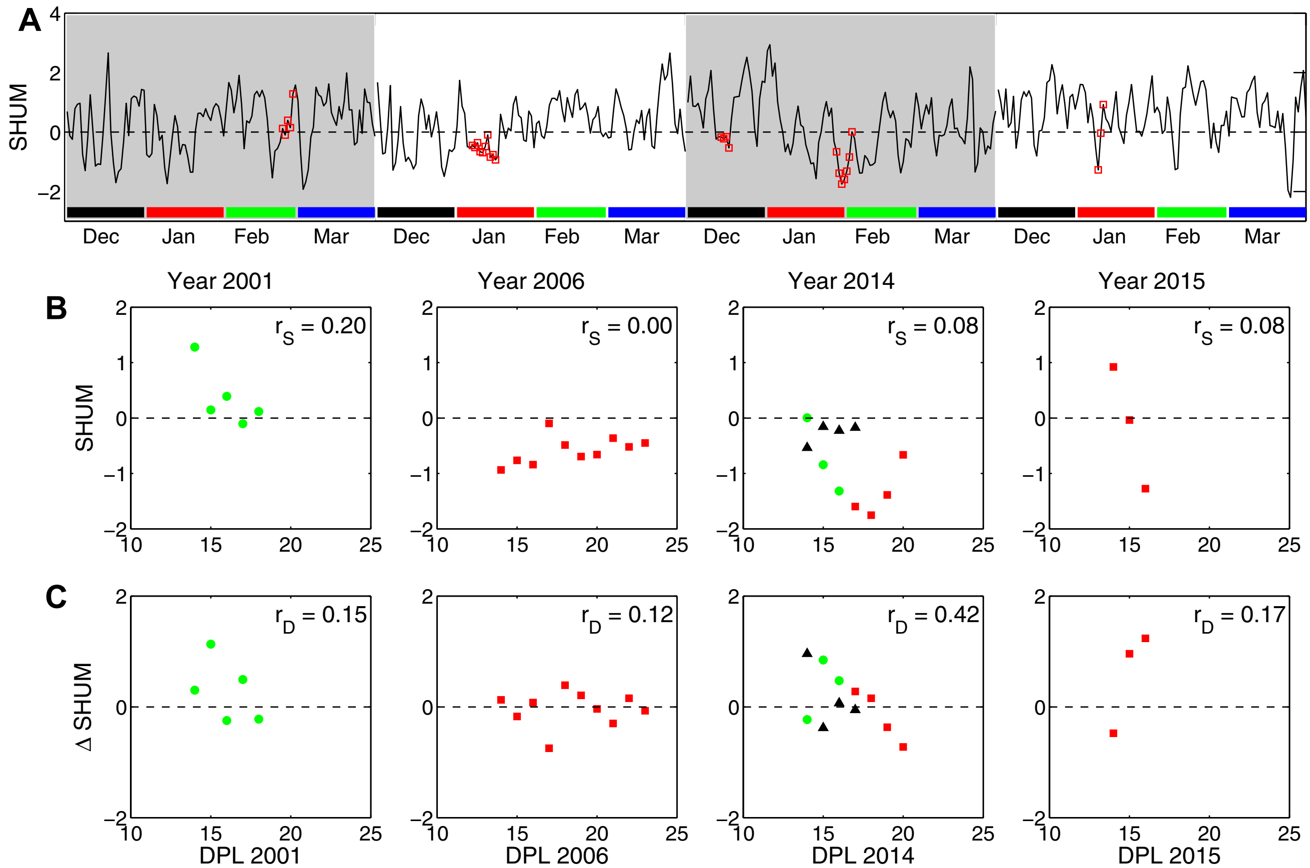

Fig. 4 Captions are similar with Fig. 3. **a** Seasonal SHUM anomaly series, **b** scatter plot of DPL and SHUM, and **c** scatter plot of DPL and $\Delta SHUM$. December (black filled triangle), January (red filled square), February (green filled circle)

which was captured by $r_D = 0.67$. In contrast, in the mild dry conditions in 2006 and 2015, the increasing trends in the SST only appeared in January which resulted in relative small values of $r_D \leq 0.25$.

Figure 6 shows the correlation of DPL to the geopotential height (GPH) at 500 hPa. Again, we first discuss the results in the original space as shown in Fig. 6b. In the very dry days in 2001, positive GPH anomaly series are observed in February only, which resulted in $r_S = 0.25$. However, in the exceptional dry days in 2014, positive GPH values were found in a much longer temporal period from December to February, which therefore yielded a much larger value $r_S = 0.56$. In the mild dry conditions in 2006 and 2015, we found positive GPH anomalies in January only, which was captured by $r_S = 0.25$. In drought events considered in all years, the relative small values of r_D in the differenced space suggested that the GPH process did not show significant changes in either increasing or decreasing trends, as shown in Fig. 6c.

For illustration purpose, we discussed the results in Figs. 1, 3, 4, 5 and 6 by defining drought events when DPL were larger than 2 weeks. Table 1 summarizes the consistent results for three different thresholds 10, 12 and 14 days. It is certain that more drought events are identified when a smaller threshold value was used, which hence changed the statistics slightly. We found that the choice of thresholds affected r_S and r_D for the very dry days in 2001, but did not change much for the results of the exceptional year 2014. For the mild dry conditions in 2006 and 2015, the results did not change much when varying threshold values.

Therefore, the averaged values over five threshold values from 10 to 14 days with step size of 1 day were summarized in Table 2. In the very dry seasons in 2001 and 2014, SLP showed significant positive anomalies when DPL was longer than the threshold with $r_S = 0.39$ and $r_S = 0.66$, respectively. However, SLP did not show clear increasing or decreasing trends since $r_D < 0.3$ in the differenced space. On the contrary, SST showed strong positive anomalies in the original space during the dry days in 2001 and 2014 with $r_S = 0.45$ and $r_S = 0.60$. In the differenced space, $r_D = 0.64$ suggested that the SST was in an extraordinary increasing phase in the exceptional drought year 2014, but SST did not show clear increasing or decreasing trends in 2001 since $r_D = 0.29$.

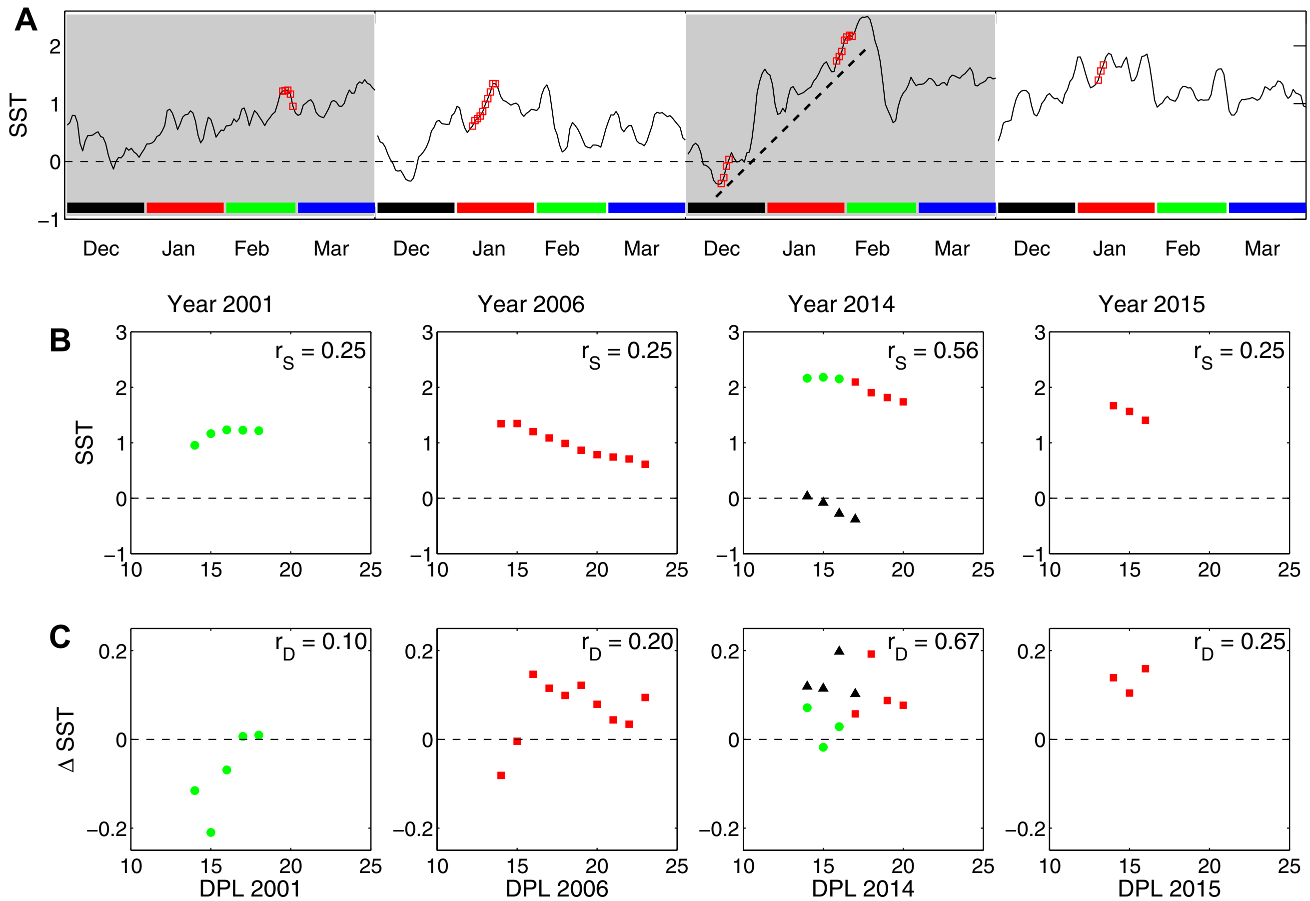

Fig. 5 Captions are similar with Fig. 3. In 2014, there was a significant number of days when SST were positive, as indicated by $r_S = 0.56$. More important, $r_D = 0.67$ suggested that the SST was in the increasing phase when DPL is larger than 2 weeks. As highlighted by the dashed line in (**a**), the increasing trend of the SST spanned from the mid of December to the early of February. The pronounced increasing phases were not observed in the other years. **b** Potential correlations in the static space, and **c** potential correlations in the dynamic space. December (black filled triangle), January (red filled square), February (green filled circle)

In both very dry seasons of 2001 and 2014, we found a significant amount of days that positive 500 hPa GPH anomalies were observed, as captured by $r_S = 0.45$ and 0.54, respectively. However, in the differenced space, small values of r_D (≤ 0.35) suggested that no clear indications for increasing trends of GPH. For the other climate variables of SHUM, we did not observe signatures for positive SHUM anomalies throughout the entire austral summers in the very dry years, which were captured by relative small values r_D.

For the mild dry seasons in 2006 and 2015, we did not find pronounced indications for positive anomalies of all considered climate variables in the original space (SLP, SHUM, SST, and GPH) since $r_S \leq 0.35$, nor in the differenced space $r_D \leq 0.30$.

5 Discussions

The southeast region of Brazil, in particular in the São Paulo area, has been predominated by precipitation deficits since 1998. In the presence of particular climate conditions in 2001, 2006, 2014 and 2015, this region experienced in austral summers of these years with extreme precipitation shortage. These extreme drought events led to a number of impacts in water availability for human consumption, agricultural irrigation and hydropower production. We study these drought events from a complex system's viewpoint, proposing to compute the expected drought period length (DPL) to disclose the distinctions of these four major drought events. We have focused more on the particular properties of the exceptional event in 2014.

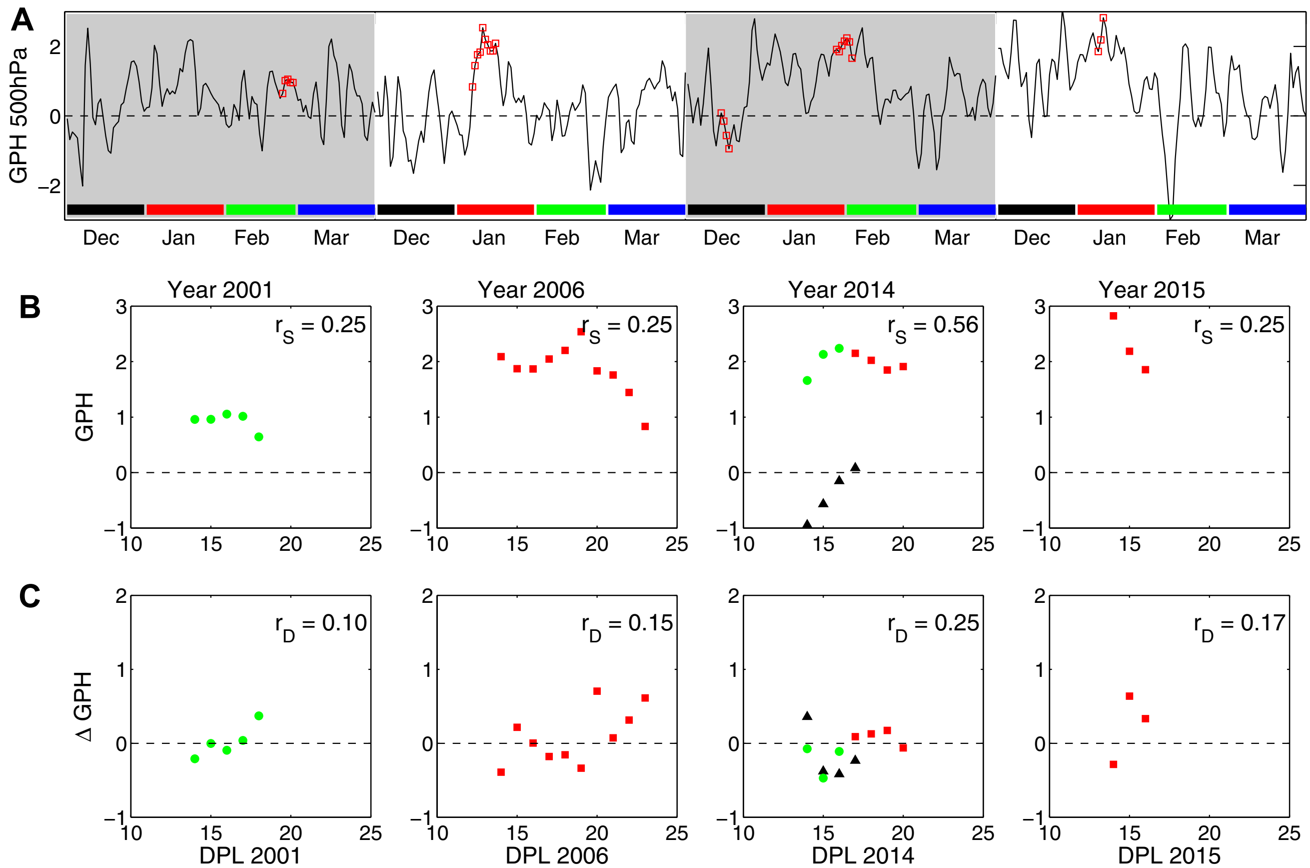

Fig. 6 Captions are similar with Fig. 3. textbfa Seasonal GPH (500 hPa) anomaly time series, textbfb potential correlations in the static space, and textbfc potential correlations in the dynamic space. December (black filled triangle), January (red filled square), February (green filled circle)

Table 1 Results of potential correlation analysis for three threshold values 10, 12, and 14 days

Year	DPL	Original space r_s				Differenced space r_D			
		SLP	SHUM	SST	GPH	ΔSLP	ΔSHUM	ΔSST	ΔGPH
2001	10	0.58	0.29	0.75	0.75	0.29	0.29	0.58	0.42
	12	0.25	0.21	0.25	0.25	0.13	0.13	0.08	0.08
	14	0.25	0.20	0.25	0.25	0.15	0.15	0.10	0.10
2006	10	0.25	0.04	0.25	0.25	0.11	0.13	0.14	0.14
	12	0.25	0.02	0.25	0.25	0.10	0.13	0.17	0.13
	14	0.25	0.0	0.25	0.25	0.10	0.13	0.20	0.15
2014	10	**0.63**	0.19	**0.63**	0.53	**0.25**	0.44	**0.63**	0.38
	12	**0.67**	0.13	**0.63**	0.54	**0.27**	0.39	**0.62**	0.37
	14	**0.69**	0.08	**0.56**	0.56	**0.27**	0.42	**0.67**	0.25
2015	10	0.42	0.43	0.50	0.50	0.26	0.23	0.39	0.14
	12	0.25	0.15	0.25	0.25	0.15	0.10	0.20	0.10
	14	0.25	0.08	0.25	0.25	0.08	0.17	0.25	0.17

An example is highlighted by bold font sizes that relative large values are observed in the original space r_S but smaller values are found in the differenced space r_D, in particular with SLP. However, large values have been obtained in both spaces of r_S and r_D for the variable SST

Table 2 Potential correlation analysis averaged over five thresholds from 10 to 14 with the step size of 1 day

Year	Original space r_s				Differenced space r_D			
	SLP	SHUM	SST	GPH	ΔSLP	ΔSHUM	ΔSST	ΔGPH
2001	0.39	0.25	0.45	0.45	0.19	0.19	0.29	0.20
2006	0.25	0.02	0.25	0.25	0.10	0.13	0.17	0.14
2014	**0.66**	0.13	**0.60**	0.54	**0.27**	0.41	**0.64**	0.35
2015	0.33	0.24	0.35	0.35	0.16	0.15	0.30	0.13

In 2014, for SLP, relative large values are observed in the original space r_S but smaller values are found in the differenced space r_D. However, for SST large values have been obtained in both spaces of r_S and r_D, which are highlighted by boldfont sizes

Based on the precipitation anomaly series over the entire time span from 2006 to 2015 (including all summers and winters), we first compute the expected DPL. The general behavior of DPL helps us to propose an exponential model to understand the occurrence frequency of drought events in the São Paulo region, which further provides insight in defining extreme drought events. This model suggests that, on average, the expected drought period length is 5 days and that the drought period might come from an independent memoryless stochastic process. This result has been further supported by the coefficient of variation C_v and the local variation of the inter-spike intervals L_v (Shinomoto et al. 2003). The four extreme drought events in the austral summers considered in this work are in the right tail of the distribution (Fig. 2) showing large deviations from an exponential behavior, which indicate that the extreme drought episodes may come from the effects of other process. To a large extent, this general property of the expected drought period length helps to define dry seasons of this region experiencing normal dry conditions.

After computing DPL, we define a drought event when the drought period is longer than some suitable thresholds (from 10 days to 2 weeks). Furthermore, we provide a systematic correlation analysis between the precipitation patterns and sea level pressure (SLP), specific humidity (SHUM), sea surface temperature (SST), and geopotential height (500hPa). The correlation analysis has been performed in two ways: (1) in the original time series space quantified by r_S, and (2) in the differencing space characterized by r_D. Note that r_D captures the increasing or decreasing trends of the anomaly series. The correlation based on trends tells us the propensity of the climatic condition changes in the region of interest, hence from a dynamic perspective. With the help of r_S and r_D, we discussed the particular climate conditions of 2014 in the context of previous years, namely, comparing the differences to other severe droughts of 2001, and mild dry seasons in 2006 and 2015.

Our method based on DPL has been verified by disclosing the blocking mechanisms of anomalous high pressure in the austral summers in the São Paulo region (Table 2). Positive anomalies of sea level pressure, specific humidity, and 500 hPa geopotential height are indicative of anomalous high pressure in this region. This high atmospheric pressure system provides an unfavorable condition for cloud development and precipitation in the southeast Brazil. In both very dry seasons in 2001 and 2014, we find that SLP and 500 hPa GPH did show clear features of high atmospheric pressure.

Furthermore, we validate the hypothesis of the roles of the anomalous warming of SST of the surrounding ocean during these drought events. The SST analysis revealed that the southwestern South Atlantic Ocean region near the coast of southeast Brazil showed a strong positive correlation with the expected drought period length, indicating that increased SST in this ocean region is consistent with reduced precipitation as observed in summer 2014. More importantly, the extraordinary increasing trend of SST in 2014 (much larger value of r_D) was not present in other drought years.

Based on these numerical analysis, we propose a hypothetical mechanism that underlies the exceptional drought event 2014 in the following sense. (1) The existence of an anomalous high pressure center in the São Paulo area acts as a blocking mechanism that prevents moisture transport from the Amazon and passage of cold front systems from the south Brazil. This is consistent with the very few observations of SACZ cases during the austral summer seasons. This blocking high has been observed in all drought seasons considered, with much larger magnitude in 2014 as captured by r_S. (2) The much faster increasing phase of the anomalous SST acts as a strong feedback to the precipitation deficit patterns in the São Paulo area. The high pressure favors the maintenance of warm SST near the coast of southeast Brazil via the direct solar radiation reaching the ocean surface. Therefore, this feedback mechanism of SST due to the blocking high pressure centered in this area acts as an enhancement factor that diverges the route of cold fronts in the south Atlantic Ocean, which further intensified the extreme climate conditions of drought 2014. Note that this unprecedented increasing trend of the SST (r_D) was not observed in other climate variables, including SLP, SHUM and 500 hPa GPH. Therefore, we conclude that the exceptional drought event of 2014 in the region of São Paulo was enhanced by the feedback mechanism of anomalous

warming of SST in the South Atlantic Oceans which resulted from the high pressure.

Although we focused on the most recent drought events in the region of São Paulo, there is a highly significant decrease of precipitation in both summer and winter seasons in the southeast Brazil starting from 1979 (Rao et al. 2016). Future work should also consider the decreasing trends of the winter seasons. In addition, we need to provide a complete picture of the distributions of anomalies of sea surface temperature in both the South Atlantic and Western Tropical Pacific (Seth et al. 2015) and the moisture sources during extreme dry events in all seasons of austral autumn, winter and spring southeastern Brazil (Pampuch et al. 2016).

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