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AGROMETEOROLOGY - Article

Impacts of climate change on drought: changes to drier conditions at the beginning of the crop growing season in southern Brazil

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ABSTRACT: The intensification of drought incidence is one of the most important threats of the 21st century with significant effects on food security. Accordingly, there is a need to improve the understanding of the regional impacts of climate change on this hazard. This study assessed long-term trends in probability-based drought indices (Standardized Precipitation Index and Standardized Evapotranspiration Index) in the State of São Paulo, Brazil. Owing to the multi-scalar nature of both indices, the analyses were performed at 1 to 12-month time scales. The indices were calculated by means of a relativist approach that allowed us to compare drought conditions from different periods. The years 1961-1990 were used as the referential period. To the authors' best knowledge, this is the first time that such relativist approach is used in historical trend analysis. The results suggest that the evapotranspiration rates have intensified the regional drought conditions. The time scale used to calculate the indices significantly affected the outcomes of drought trend assessments. The reason behind this feature is that the significant changes in the monthly regional patterns are limited to a specific period of the year. More specifically, virtually all significant changes have been observed during the first trimester of the rainy season (October, November and December). Considering that this period corresponds to critical plant growth stages (flowering/regrowth/sprouting) of several major crops (e.g. Sugarcane and Citrus), we may conclude that these significant changes have increased the risk of crop yield reductions due to agricultural drought.

Key words: intensification of drought, drought Index, agricultural drought, crop yields.

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INTRODUCTION

Providing food security for an increasing world population under transient climate conditions has been one of the great challenges faced by the agricultural sector (Rosenzweig and Parry, 1994; Ray et al. 2015; Beddington et al. 2012; Challinor et al. 2014). The degree of dependence on natural resources (Thornton et al. 2014) and the impact of climate change on drought incidence play a key role in amplifying this challenge. Accordingly, possible global intensifications of drought conditions (Dai 2012) is of great concern for any agricultural area. This is particularly true for tropical developing countries because of their high dependence on rainfed systems (Rockström et al. 2010; Rost et al. 2009). This is the context for the State of São Paulo, Brazil where the agriculture represents 15% of the state gross domestic product (GDP) (CEPEA 2013) and is heavily based on rainfed systems. For instance, the 2014/2015 crop season was marked by an extreme drought event in the State of São Paulo (Nobre et al. 2016), that caused to the citrus sector a yield reduction of 13% and an economic loss of U$235 million (USDA - Foreign Agricultural Service 2015). Previous studies already evaluated the precipitation variability in the State of São Paulo indicating a possible delay in the rainy season onset (Blain and Bardin-Camparotto 2014) and increases in extreme precipitation events (Dias et al. 2012). However, none of these studies assessed trends in drought conditions quantified through probability-based indices currently used to monitor drought conditions. Moreover, climate models predictions suggest severe drought conditions in the late half of 21st century over several areas of the world including Brazil (Dai 2012). These projections are consistent with the observed global intensification of drought conditions derived from drought indices and environmental variables such as the difference between precipitation and evaporation (Dai 2012). They also agree with crop model simulations that project an increase in global irrigation requirements (Levis et al. 2016).

With regards to drought quantification, the scientific literature frequently recognizes three types of physical drought – agricultural, meteorological and hydrological – and a fourth type of non-physical drought: the socioeconomic (Wilhite and Glantz 1985; Smakhtin and Schipper 2008; Mishra and Singh 2010; Hao and Singh 2015). An agricultural drought is supposed to be established when the shortage of soil moisture adversely affects the regional agricultural production due to evapotranspiration losses that have not been properly replaced (Mannocchi et al. 2009). Under this type of drought, even on a relative short period of water deficit during critical growth stages (e.g. flowering and fruit set) can cause irreversible damages to crop yields. This statement is particularly true for rainfed systems.

With regards to drought time series, the Standardized Precipitation Index (SPI) is a probability-based index developed to quantify precipitation departures over different time scales (Mckee et al. 1993)[3] making them invariant in both time and space.

It has been widely used in both operational and academic mode (Wu et al. 2007). However, because the SPI uses only precipitation amounts, this index is not capable of including the effect of temporal changes in evapotranspiration rates on drought quantification (Vicente-Serrano et al. 2010). The Standardized Evapotranspiration Index (SPEI) was designed by Vicente-Serrano et al. (2010) to include such effect on drought evaluations. As the Palmer Drought Severity Index (PDSI) (Palmer 1965) and the Self-calibrated Palmer Drought Severity Index (scPDSI) (Wells et al. 2004), the SPEI takes into account the effect of the reference (or potential) evapotranspiration on drought occurrence (Beguería et al. 2014).

Nevertheless, different from the PSDI and scPDSI, the SPEI overcomes the problem of presenting an inherent fixed time scale (Chen and Sun 2015) because it uses the same multi-scalar algorithm as the SPI. Vicente-Serrano et al. (2015) compared the sensitivity of several drought indices to precipitation and reference evapotranspiration variations. These authors concluded that the low sensibility of the Palmer indices to different evapotranspiration rates limits their use in applications addressing changes in this agrometeorological parameter. On the other hand, Vicente-Serrano et al. (2015) indicated that the SPEI showed the largest sensitivity to changes in evapotranspiration rates.

Therefore, assuming that the trend analyses of drought time series is an essential step for understanding regional impacts of global climate changes on agricultural production (Hayhoe et al. 2007), this study assessed trends in long-term SPI and SPEI series in the State of São Paulo. Owing to the →

[3]Mckee, T.B., Doesken, N. J. and Kleist, J. (1993).The relationship of drought frequency and duration to time scales. In Proceedings of the 8th Conference of Applied Climatology, Anaheim, CA. (p. 179-184). Boston: American Meterological Society.

multi-scalar nature of both indices, the trend analyses were performed at 1 to 12-month time scales.

MATERIAL AND METHODS

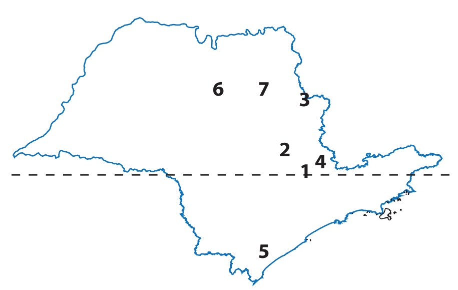
Material

The State of São Paulo is crossed by the Tropic of Capricorn (lat 19°–26°; long 53° – 44° W). Its climate variability is influenced by monsoon system (Carvalho et al. 2013). As others Southeastern regions of Brazil, the onset of the rainy season in State of São Paulo typically occurs between September and October (Vera et al. 2006). The maximum precipitation occurs during the austral summer associated with the South Atlantic Convergence Zone and in the winter predominates the high pressing system of the South Atlantic. This State is regarded as a global agricultural hotspot mostly because the sugarcane and citrus production. The sugarcane industry in the State of São Paulo had a revenue of 30 billion USD in 2012 and employed 1 million workers (Moraes et al. 2015), representing 60% of the national production. The citrus industry presents similar socio-economic importance representing 30% of the world production (USDA – Foreign Agricultural Service 2015).

The meteorological data were obtained from the Agronomic Institute (IAC/APTA/SAA). The weather stations (Figure 1) were selected because they can support trend analyses that include the normal period (1961-2015), present no missing data and their consistencies have already been evaluated in previous studies (Blain 2011; Blain 2013; Blain and Bardin-Camparotto 2014; Meschiatti and Blain 2016). These stations also represent climatically dissimilar areas ranging from the coastal area (Pariquera – Açú), where there is virtually no dry season, to the northwestern region (Pindorama and Ribeirão Preto), where there is a distinctly dry season during the austral winter.

METHODS

The SPI calculation starts by fitting a parametric distribution to the precipitation data (P) that can be accumulated over a wide range of time scales (Dutra et al. 2014). This first step is also known as calibration process (Dubrovsky et al. 2008). The index final value is obtained by applying the inverse standard normal function to the cumulative probabilities (Guttman 1999) so that the distribution of the index values is approximately the same for any precipitation series (Dubrovsky et al. 2008). This latter statement holds either when the



Weather stations at São Paulo State	Lat (S)	Lon (W)	Alt (m)
1 – Campinas	22°54’	47°05’	669
2 – Cordeirópolis	22°32’	47°27’	639
3 – Mococa	21°27’	46°59’	665
4 – Monte Alegre do Sul	22°42’	46°39’	777
5 – Pariquera-Açu	24°43’	47°52’	68
6 – Pindorama	21°13’	48°54’	562
7 – Ribeirão Preto	21°11’	47°48’	620

Figure 1. Weather stations used in this study.

calibration process is applied to all available data or when there is no change in the underlying precipitation distributions among distinct analyzed periods (Wu et al. 2005; Dubrovsky et al. 2008). In this study, the 2-parameter gamma distribution was used to fit the frequency distribution of precipitation data as suggested by several authors, including Stagge et al. (2015) and Meschiatti and Blain (2016). This 2-parameter distribution is also used by the drought monitoring systems of several Brazilians institutions such as *Empresa Brasileira de Pesquisa Agropecuária* and *Instituto Nacional de Meteorologia*. Originally, the SPI calculation algorithm assigns the largest possible index value for the zero precipitation amount. This method truncates the SPI distribution at increasingly higher values limiting its ability to represents droughts (SPI < –1.0) and floods (SPI > 1.0) events in a similar way. Stagge et al. (2015) addressed this issue by adopting the "center of mass" of the zero distribution. The concept of "probability mass" related to the SPI calculation (adopted in this study) is described in Solakova et al. (2014).

The SPEI is based on the same algorithm as the SPI. However, its input variable is the difference (PEP) between precipitation and reference evapotranspiration (EP) (Beguería et al. 2014). Considering the climate conditions of the State of São Paulo and the lack of at-site meteorological data such as wind speed and net radiation, the Thornthwaite's method was used to estimate the monthly EP amounts. In spite of its documented limitations, the Thornthwaite model is suited to estimate EP values in the State of São Paulo at time scales equal to or greater than one month (Camargo and Camargo 2000). The generalized logistic, as suggested by Beguería et al. (2014), was used to fit the PEP series. The suitability of the two above-mentioned distributions for calculating each index at all time scales was evaluated through the Shapiro-Wilk test (Stagge et al. 2015). The SPI and SPEI values may be classified into categories that express a severity of an event with respect to normal conditions at a given site. These categories span from extremely dry (SPI ≤ −2) to extremely wet (SPI ≥ 2), with normal conditions falling within (−1, +1). In this study, while SPI/SPEI values equal to or lower than – 1.0 are referred to as dry events, SPI/SPEI values equal to or greater than 1.0 are referred to as wet events.

The relativist approach

The relativist approach (Dubrovsky et al. 2008) improves the use of standardized drought indices in climate change studies. By adopting a referential period or a referential series, it can be used either to compare drought conditions at different sites during a given period or to compare drought conditions for a single site during different periods. This study adopted the normal period (1961-1990) to calibrate both SPI and SPEI distribution parameters. Accordingly, changes in drought incidence were evaluated for each weather station in respect to the normal period. To the authors' best knowledge, this is the first time that such approach is used in historical trend analysis and it can be calculated as follow:

$$H(P) = \begin{cases} \Pr(P=0) + [1-\Pr(P=0)\,Gamma(P>0;\lambda), & P>0 \\ \Pr(P=0), & P=0 \end{cases} \quad (1)$$

$$H(PEP) = GL(PEP;\lambda) \quad (2)$$

where

$$\Pr\,(\mathrm{P}=0) = \frac{n_p+1}{2(n+1)} \quad (3)$$

Gamma (.) and GL (.) are, respectively, the cumulative density function of the 2-parameter gamma and generalized logistic distributions; λ is the parameters of the distributions calculated from the normal period (1961-1990); $n_p = 0$ is the number of zero precipitation values (P = 0) in the normal period; n is the total number of data in the normal period.

The final step of the SPEI (SPI) algorithm consists in applying the following rational approach (Abramowitz and Stegun, 1965; equiprobability transformation) to H(.).

$$\begin{aligned} \mathrm{SPEI\,(SPI)} &= -\left(\mathrm{t} - \frac{\mathrm{co} + \mathrm{c_1 t} + \mathrm{c_2 t^2}}{1 + \mathrm{d_1 t} + \mathrm{d_2 t^2} + \mathrm{d_3 t^3}}\right) \text{ when } 0 < \mathrm{H(.)} \leq 0.5 \\ \mathrm{SPEI\,(SPI)} &= +\left(\mathrm{t} - \frac{\mathrm{co} + \mathrm{c_1 t} + \mathrm{c_2 t^2}}{1 + \mathrm{d_1 t} + \mathrm{d_2 t^2} + \mathrm{d_3 t^3}}\right) \text{ when } 0.5 < \mathrm{H(.)} < 1 \end{aligned} \quad (4)$$

where co = 2.515517; c_1 = 0.802853; c_2 = 0.010328; d_1 = 1.432788; d_2 = 0.189269; d_3 = 0.001308

$$\begin{aligned} \mathrm{t} &= \sqrt{\left(\ln\Big(\frac{1}{(\mathrm{H(.)})^2}\right)} \quad \text{for } 0.5 < \mathrm{H(.)} < 1 \\ \mathrm{t} &= \sqrt{\left(\ln\Big(\frac{1}{(1-\mathrm{H(.)})^2}\right)} \quad \text{for } 0 < \mathrm{H(.)} \leq 0.5 \end{aligned} \quad (5)$$

The Mann-Kendall trend test (MK) (Kendall and Stuart 1967) was used to assess the significance of the trends in all SPI and SPEI series. Positive or negative MK values indicate the presence of increasing or decreasing trends. Although this test has been widely used to detect trends in geophysical time series, it was originally designated for uncorrelated data (e.g. Yue et al. 2002). In this study, all time series (1 to 12-month) were built/analyzed so that the time span between two consecutive data is one year. Therefore, we assumed no significant serial correlation. All analyses were performed at the 5% significance level.

RESULTS AND DISCUSSION

Considering the normal period, the gamma and generalized logistic can be used to calculate the SPI and SPEI, respectively. The rejection rates of the Shapiro-Wilk test, applied to both indices, were lower than the adopted significance level for all locations. Considering short time scales (≤ 3-month), the indices exhibit similar patterns of wet/dry events in the State of São Paulo (Figure 2). This finding agrees with those pointed out by Lloyd-Hughes and Saunders (2002) that stated that the occurrence of drought events in a given region are primarily controlled by the precipitation variability. However, the SPEI presented higher numbers of significant trends as well as higher numbers of negatives MK values. Considering the calculation algorithm of these two indices, this feature suggests that the evapotranspiration rates have been puttting pressure over the drought events toward more severe conditions. Therefore, it should not be neglected in drought modeling (Zarch et al. 2015) as well as in drought trend assessments (Chen and Sun 2015) in the State of São Paulo.

With regards to the question posed in section 1, the trend analysis suggests an important change to drier-than-normal conditions during the first trimester of the regional rainy season. Particularly for the month of October, which may be regarded as the first month of the growing season for several major crops, all locations presented negative MK values for both 1-month-SPI and 1-month-SPEI series. Considering these SPI (SPEI) series, four (five) locations presented significant changes to drier-than-normal conditions. As for the monthly time scale, the analyses performed at the other short time scales (2 and 3-month) also revealed significant changes to drier-than-normal conditions in the onset of the crop growing seasons. This latter inference is particularly noticeable for the SPEI series due to the higher number of significant MK values. For instance, all 2-month SPI and SPEI series of October and November presented negative MK values. Considering these two 2-month series, the SPEI presented seven significant decreasing trends while the SPI presented only three. The analysis also suggests that the negative MK values observed for the 2-month SPI and SPEI series of November are in general the result of significant decreasing trends observed in the 1-month series of October. This is particularly true for the SPI because the monthly series of November presented no significant MK value, with only one location (Monte Alegre do Sul) presenting MK < 0. With regards to the 3-month time scale, all SPI and SPEI series of October, November and December presented negative MK values (Figure 2). However, different from the series of November, there is a high concentration of MK < 0 values for both 1-month SPI and SPEI series of December. Therefore, the significant decreasing trends found in the 3-month series of December are in general the result of significant changes to drier-than-normal conditions observed in the months of October and December. Finally, considering that:

i. For truly independent and identically distributed data the MK statistic is expected to randomly range over zero (Blain 2012; Blain and Bardin-Camparotto 2014), showing no concentration of negative values in a particular period and region;
ii. The high number of significant decreasing trends found in the monthly series of October and;
iii. The fact that the analyzed trimester match with critical growth stages of several crops (Carr 2012), we indicate the presence of changes in the climatic patterns of the crop growing season that should be considered in public policies such as the crop zoning.

The analyses performed at other time scales (4 to 12-month) are consistent with those depicted in Figure 3, adding little information to the trend assessment. The SPEI presents (again) a higher number of significant trends than the SPI does (Figure 3). This feature further supports the statement that the evapotranspiration rates are intensifying the drought conditions in the State of São Paulo. In fact, the results depicted in Figure 3 (SPI series) indicate a lack of significant trends in the precipitation amounts accumulated at time scales equal to or greater than four months for practically all locations of this →

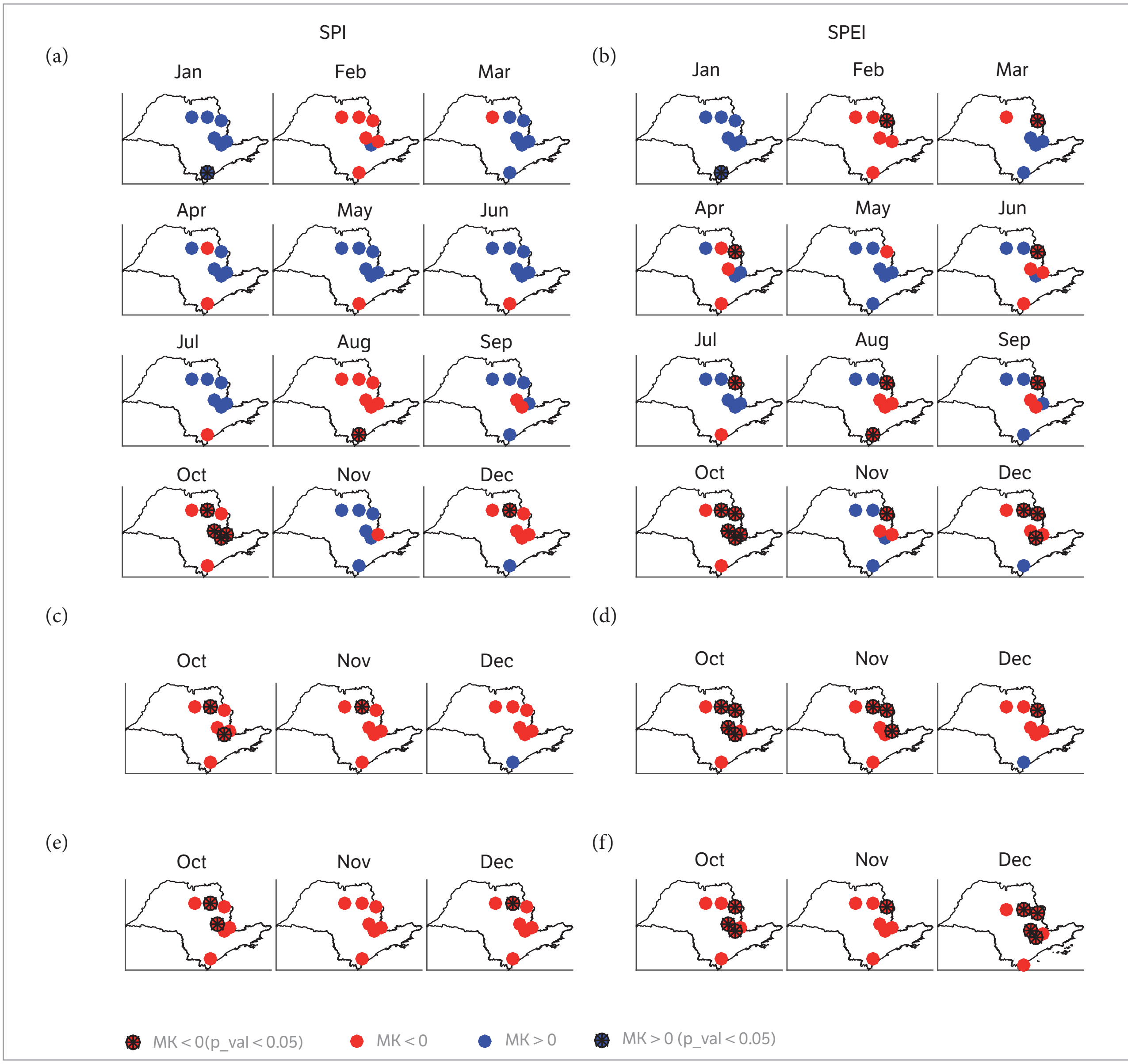


Figure 2. Mann-Kendall trend test applied to SPI (a,c and e) and SPEI (b,d and f) series at 1(a,b), 2 (c,d) and 3 (e,f) month time scales (5% significance level). State of São Paulo.

study. Considering time scales greater than 10 months, no significant MK value is observed for both SPI and SPEI series. This latter result agrees with Spinoni et al. (2014) that found no significant trend in 12-month SPI series in southeast region of Brazil. It also indicates that when the significant trends are limited to a specific period of the year (e.g. the onset of the rainy season) trend analyses based on the SPI/SPEI become strongly affected by the time scale. In other words, while the regional trend analysis performed at short time scales (e.g. 1 to 3-month) agree with studies indicating a global intensification in drought conditions (Dai 2012), the analyses carried out at large time scales (e.g. 10 to 12-month) are consistent with studies describing the presence of no trend in the drought patterns of Southeast South America (Spinoni et al. 2014).

The significant trends found at 1 to 3-month time scales are further evaluated in Figure 4, which depicts the difference between the frequencies of dry and wet events observed between the periods of 1991-2015 and 1961-1990. Again, the analyses based on the SPEI display greater intensifications in the drought conditions than the SPI does. As exemplified for the 1-month (3-month) SPEI

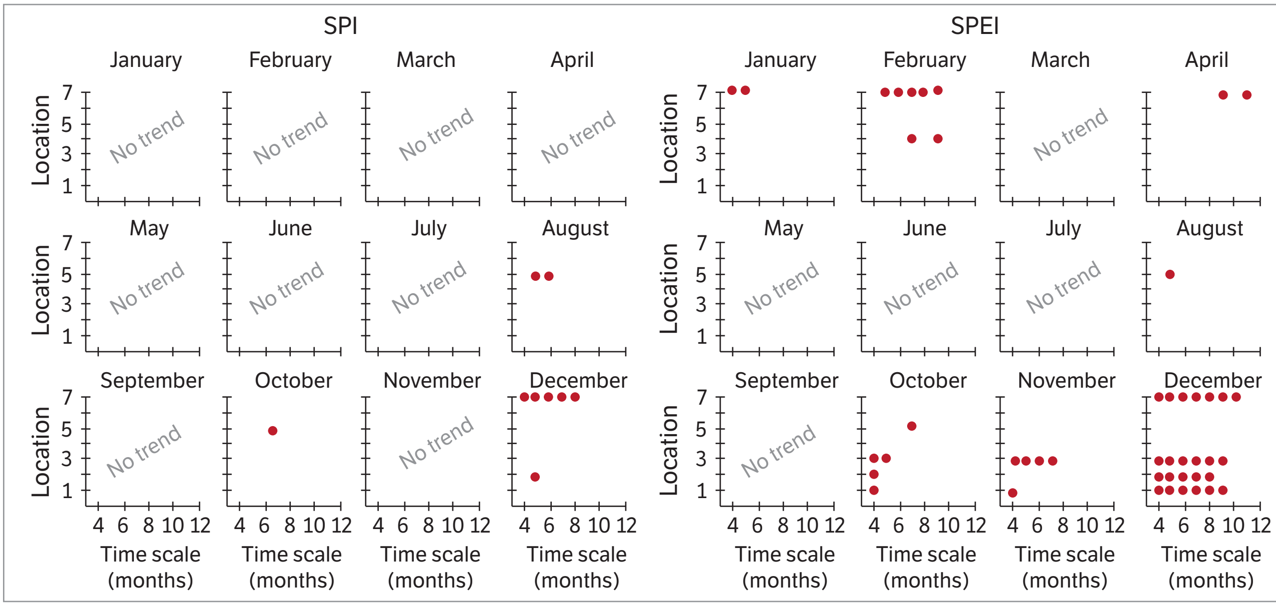


Figure 3. Mann-Kendall trend test for 4-12 time scales. The red circles represent significant decreasing trends at 5% level.

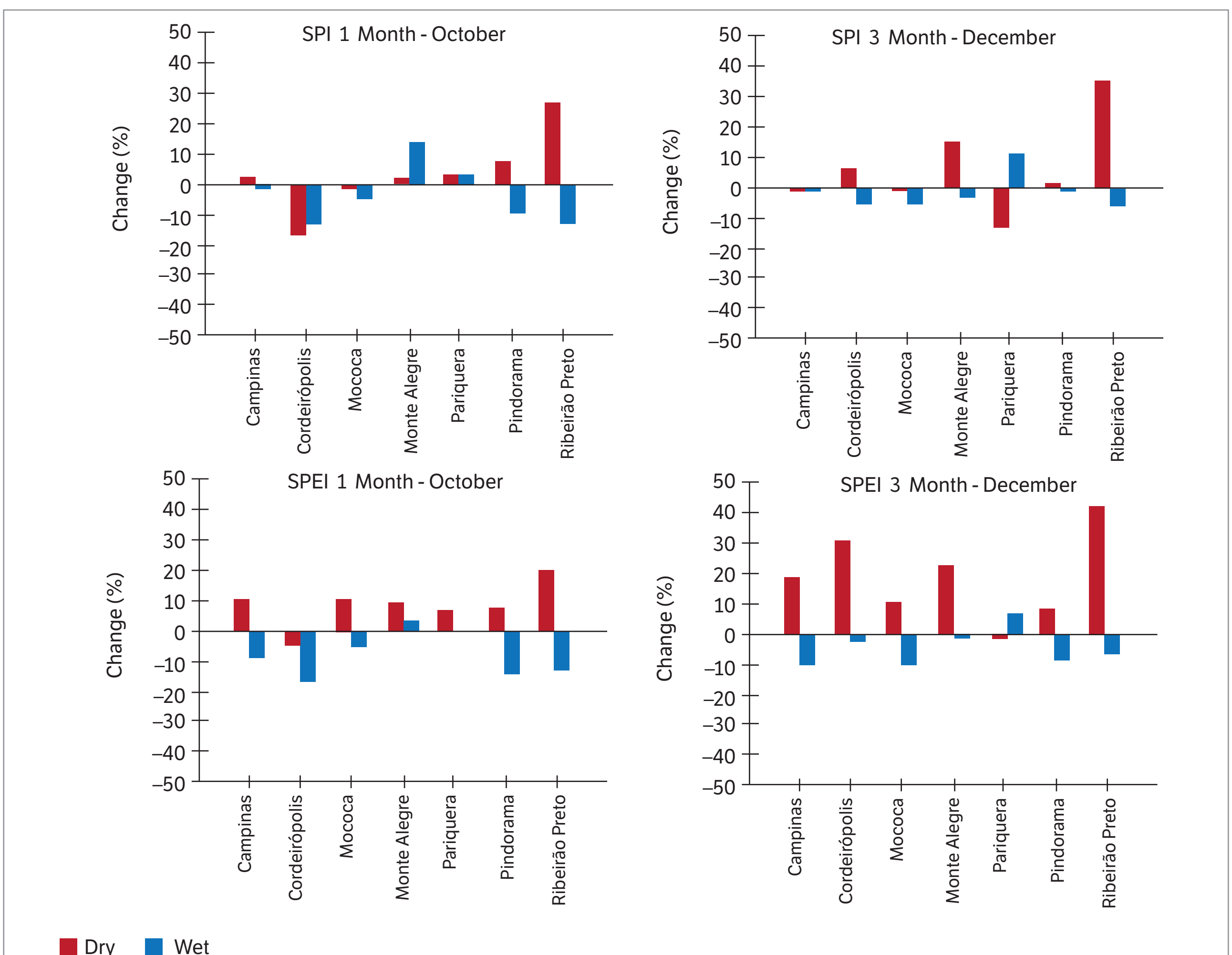


Figure 4. Changes in Dry and wet events.1991-2015 in respect to 1961-1990. The red (blue) bars represent the change in the dry (wet).

series of October (December) virtually all locations presented an increase in the frequency of dry SPEI events (Figure 4, red bar). For the 1-month time series, Cordeirópolis is the only location presenting a decrease in the frequency of SPEI dry events. Naturally, this behavior seems to be in disagreement with the significant negative MK values found in this location. However, the analysis of the wet events (Figure 4, blue bar) indicates that Cordeirópolis presented the highest decrease in the SPEI-Wet events (from 20 to only 4%). This behavior, also observed for the 1-month SPI series of Cordeirópolis, led to the significant negative MK values observed in this location. Finally, the analysis of Figure 4 also agrees with the assumption that the evapotranspiration rates have been putting pressure over the drought events in the State of São Paulo. This assumption is supported by the fact that the changes in the frequencies of SPEI-Dry events are higher than the frequencies of the SPI-Dry events for all locations, apart from the monthly series of Ribeirão Preto. This latter sugarcane producing region presents the highest changes to drier conditions among all locations. This remarkable regional intensification on drought occurrence is of particular concern because, as other locations of the State of São Paulo (Marin et al. 2013), the sugarcane production in Ribeirão Preto is heavily based on rainfed systems. The frequency analysis performed at 2-month time scales leads to equivalent results as those exemplified in Figure 4. As for the 1 and 3-month time scale, the frequencies of SPEI-Dry events (1991-2015) are higher than the frequencies of 2 and 3-month SPI-Dry events (1991-2015) for all locations.

FINAL REMARKS

This study evaluated trends in drought events that may negatively affect the agricultural production of the State of São Paulo, one of the most important Brazilian agribusiness regions. The study was based on widely used probability-based drought indices (SPI and SPEI) calculated under a relativistic approach proposed by Dubrovsky et al (2008). The use of both indices allowed us to conclude that the evapotranspiration rates have been putting pressure over the regional drought incidence toward more severe conditions. The results also indicated that trend analyses based on multi-scalar drought indices may be strongly affected by the time scale adopted in their calculation. While the analyses performed at 1 to 3-month time scales revealed significant increasing trends in the drought occurrence in all locations of the study, the analyses carried out at time scales greater than 10 months indicate the presence of no trend in all weather stations. The reason behind this feature is that the significant changes in the monthly regional patterns are limited to a specific period of the year (virtually all significant changes were observed in the first trimester of the reginal rainy season). Considering that this latter period frequently corresponds to critical growth stages of several major crops (e.g. Citrus and Sugarcane), this increase in the frequency of dry events have enhanced the risk of crops failure due to agricultural drought, deserving to be considered in public policies such as the crop zoning. Our results are also consistent with other studies describing a global intensification of drought events due to decreases in precipitation patterns and/or increases in evapotranspiration rates (e.g. Dai 2012).

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