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Long-term variation of PDSI and SPI computed with reanalysis products

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Abstract: Long-term temporal variation of droughts in Portugal was assessed using the Palmer Drought Severity Index (PDSI) and the Standardized Drought Index (SPI) with a 9 month time scale. Weather data from the NOAA-CIRES Twentieth Century Reanalysis Project version 2c, which spans from 1851 to 2014 with a spatial coverage of 2.0º latitude x 2.0º longitude were used. For PDSI, monthly evapotranspiration was computed using the FAO PM-ET_o method. Monthly data from reanalysis products consisted of maximum and minimum air temperature, net radiation, wind speed and relative humidity. Precipitation data was obtained from the same source. To assess how the long-term climate variability influences the identification of dry events in the drought indices, five different calibration periods were selected to estimate, respectively the potential values of evapotranspiration, runoff, soil moisture recharge and percolation loss of the PDSI water balance and the distribution function parameters of the SPI. Results show that the adopted calibration period have a significant impact of the frequency of extreme events detected in both drought indices. A Fourier analysis was applied to PDSI and SPI time series to search for significant cycles that could relate to return periods of droughts, with North Atlantic Oscillation cycles previously identified for Portugal.

Key words: PDSI; SPI; long-term variability; 20th century reanalysis

1. INTRODUCTION

Drought indices (DI) are the most usual tools to assess drought characteristics (severity, duration and magnitude). Most used are the Palmer Drought Severity Index (PDSI; Palmer, 1965) and the Standardized Precipitation Index (SPI; McKee et al., 1993). PDSI combines precipitation and evapotranspiration in a simple soil water balance to define a deviation from normal conditions, while SPI requires precipitation data only and it is obtained by adjusting a probability distribution function (pdf) to the precipitation cumulated over a defined number of months. Thus, the SPI depends on the time scale and calibration period (CP) considered to estimate the pdf parameters. Paulo et al. (2016), using long-term time series of precipitation in Portugal, from 1863 to 2007, showed that long-term precipitation variability influences SPI and highlighted the importance of the reference period considered to estimate pdf parameters, especially for non-stationary precipitation time series.

Such long-term variability of climate may also have an influence on PDSI. Thus, herein PDSI and SPI, the latter computed at 9 month time scale (SPI-9) because it compares better with PDSI (Paulo et al., 2012), were computed using long records of monthly precipitation, and reference evapotranspiration (PM-ET_o; Allen et al., 1998). Data were obtained from the NOAA-CIRES Twentieth Century Reanalysis Project, (20th-century reanalysis, Compo et al., 2011), which spans from 1851 to 2014 with a spatial resolution of 2.0º latitude x 2.0º longitude. In this study, both PDSI and SPI-9 were computed with the reanalysis data for Portugal considering 5 CP to assess the impacts that different CP have on the PDSI and SPI-9 time series. To assess the quality of those computations, the SPI and PDSI obtained from reanalysis were compared with PDSI and SPI-9 time series computed with long records of observed precipitation and PM-ET_o data retrieved from the Climate Research Unit (CRU) project (Harris et al., 2014). The aim of this study is (1) to assess the accuracy of the reanalysis data to estimate the PDSI and SPI; (2) assessing the impact of the CP used on both DI; (3) searching for significant cycles of drought occurrence, using spectral analysis applied to the 164 years of data of 20th-century reanalysis.

2. DATA AND METHODS

To study the impacts of long-term variability of precipitation and ET_o on drought assessment by the SPI and PDSI, monthly records of precipitation rate (kg m^{-2} s^{-1}), maximum and minimum temperature (K) , downwards shortwave radiation (W m^{-2}), meridional (v) and zonal (u) wind components, both at 10 m height (m s^{-1}), specific humidity (kg kg^{-1}) and surface level pressure (kPa) from NOAA-CIRES 20th-century reanalysis were retrieved for the period 1851-2014.

ET_o, used in the water balance of the PDSI was computed using the PM-ET_o equation because it is preferable than using temperature methods to describe climate variability (Ren et al., 2016a,b). Results from Martins et al. (2016) showed that, overall, reanalysis data are suitable for PM-ET_o estimation in a monthly time-scale for the Iberian Peninsula. To calculate ET_o, wind speed was computed using zonal u and meridional v components at 10 m height converted to 2 m. Relative humidity (%) was obtained from the temperature data, specific humidity and surface level pressure.

To assess the accuracy of the reanalysis based PDSI and SPI, both indices were also computed with long records (1911-2007) of precipitation from weather stations and PM-ET_o from the CRU TS3.21 (Harris et al., 2014) with data of the same period. Those data were previously used to assess long-term variability of droughts in Portugal (Moreira et al., 2012; Paulo et al., 2016). Fig. 1 depicts the spatial distribution of the three groups of data. Precipitation and ET_o values from the CRU grid were interpolated to the coarser grid mesh of the reanalysis in order to obtain comparable datasets. The observed PDSI and SPI were computed for the common period of 1911-2007.

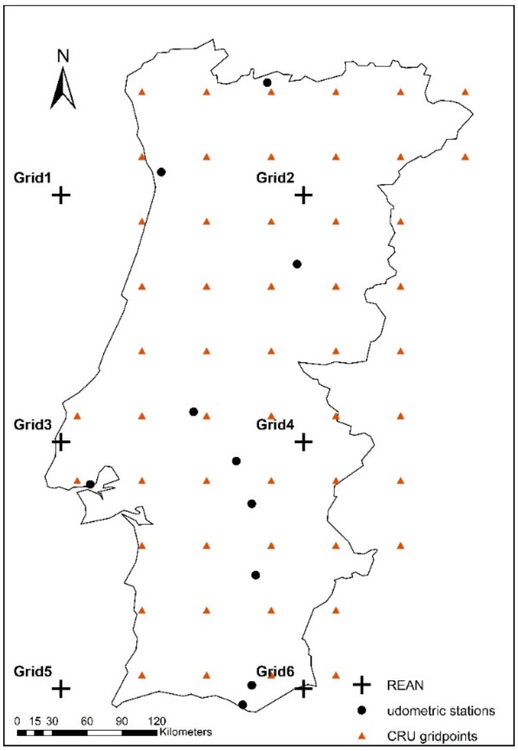

Figure 1. Distribution of the 20th-century reanalysis (REAN) grid-points, weather stations and CRU grid-points.

The SPI-9 was computed following the procedure proposed by Edwards (2000) with the Gamma pdf parameters being estimated with unbiased probability weighted moments.

The PDSI is based on a supply-and-demand concept of the soil water balance applied to a twolayer soil (Palmer, 1965). The index computes a moisture departure, i.e., the difference between actual precipitation and the precipitation expected to occur for the average conditions of the climate through the computation of a monthly water balance and the calibration of local monthly coefficients for the various terms of the soil water balance. Thus, four values related to the water balance - evapotranspiration (ET), recharge (R), runoff (RO) and loss (L) - and the respective multiplier parameters (α, β, γ and δ) used to obtain the potential values are computed for each month of the year. These potential values of the water balance are, thus, the ones which are 'climatically appropriate for existing conditions' (CAFEC). The selection of the period to estimate the CAFEC potential may impact the PDSI index. In this study the water balance was computed considering a soil water holding capacity of 150 mm, with 25 and 125 mm, respectively in the first and the second layer.

PDSI and SPI-9 were computed with the 20th-century reanalysis time series for the period 1851-2014, using five different CP of 40 years' length each: 1851-2014, 1851-1891, 1892-1932, 1933-1973 and 1974-2014. This approach aimed at assessing the impact of the CP used to estimate the Gamma pdf parameters of the SPI-9 and the potential values of the PDSI.

Additionally, drought cyclicity was analyzed for PDSI and SPI-9, using spectral analysis, and results were compared to those obtained by Moreira et al. (2015) who used Fourier analysis applied to time series of SPI-12 of 66 years.

3. RESULTS

3.1 Time variability of precipitation and ET_O

To search for changes in the long-term variability of time series of precipitation and ET_o in the six grid-points (P_{REAN} and $ET_{o\text{-}REAN}$) used in this study, the mean value and the standard deviation were computed for the entire period of data (1851-2014) and to each period of 40 years (Table 1). Results in Table 1 show that the variability of P_{REAN} is enormous, with a variance close to the mean, while the variability of $ET_{o\text{-}REAN}$ is smaller. In the 164 years analyzed, the lowest values of both of the mean and variance of the precipitation were observed in the latest period (1974-2015) in all the grid-points, which is consistent with the negative precipitation trend over Iberian Peninsula related to more frequent North-Atlantic Oscillation (NAO) positive phases (Puebla and Nieto, 2010). The periods 1892-1932 and 1933-1973 were the wettest periods, both in terms of mean and variance of precipitation. ET_o variability changes little throughout the period with a slow increase in both mean value and variability over the years.

Table 1. Comparison of mean (μ) and standard deviation (σ^2) of reanalysis precipitation and ET_o in each grid-point for the five calibration periods.

	1851-2014		1851-1891		1892-1932		1933-1973		1974-2014	
	μ	σ^2	μ	σ^2	μ	σ^2	μ	σ^2	μ	σ^2
Precipitation (mm month^{-1})										
Grid1	70.8	70.5	70.8	71.2	74.2	68.6	74.7	73.9	63.3	67.6
Grid2	78.3	73.4	77.0	74.7	80.5	70.0	83.6	77.9	71.9	70.5
Grid3	60.4	68.3	60.4	70.2	62.3	67.1	64.5	69.7	54.5	65.8
Grid4	65.0	72.6	63.5	74.9	65.6	69.7	70.6	75.5	60.2	69.7
Grid5	45.7	57.2	45.8	59.7	46.8	55.1	49.0	57.3	41.2	56.3
Grid6	43.5	56.5	42.0	58.2	43.9	53.6	48.1	59.6	40.2	54.2
ET_o (mm d^{-1})										
Grid1	2.8	1.3	2.7	1.3	2.7	1.2	2.8	1.3	2.8	1.2
Grid2	2.9	1.3	2.8	1.4	2.8	1.3	2.9	1.3	2.9	1.3
Grid3	3.2	1.3	3.2	1.4	3.2	1.3	3.3	1.3	3.3	1.3
Grid4	3.3	1.3	3.2	1.4	3.2	1.3	3.3	1.3	3.3	1.3
Grid5	3.6	1.3	3.6	1.4	3.6	1.3	3.7	1.3	3.7	1.3
Grid6	3.6	1.3	3.6	1.4	3.6	1.3	3.7	1.3	3.7	1.3

3.2 Comparing the 20th-century reanalysis with observations

P_{REAN} and $ET_{o\text{-}REAN}$ were compared with the respective grid-points obtained from the average of the observed precipitation and ET_o (P_{OBS} and $ET_{o\text{-}OBS}$) in the grid area of the 20th-century reanalysis, for the common period between 1911-2007 (Table 2) using a set of statistical diagnostics. These indicators were previously applied to compare monthly ET_o estimated from reanalysis data with ET_o estimated from observations (Martins et al., 2016) and are defined by these authors.

P_{REAN} was largely underestimated in 4 out of 6 grid-points with negative percent bias (PBIAS) reaching 40% (Table 2). However, P_{REAN} in Grid4 overestimates considerably those of observations. Only for Grid3 a fairly good fit was observed between P_{REAN} and P_{OBS}, but still having considerable large estimation errors (30.22 mm/month). $ET_{o\text{-}REAN}$ overestimates $ET_{o\text{-}OBS}$ but are closer, in mean, to the observed values with smaller bias (Table 2). Results for the modelling efficiency EF relative to both P_{REAN} and $ET_{o\text{-}REAN}$ show that the approach used is adequate since EF exceed 0.55, thus indicating that the mean square errors of estimates are much higher than the variance of observations.

Table 2. Performance indicators relative to the comparison between P_{REAN} and $ET_{O\text{-}REAN}$ against P_{OBS} and $ET_{O\text{-}OBS}$.

	b	*a**	*b_0*	*R^2*	*RMSE**	*EF*	*PBIAS*
P_{OBS} vs P_{REAN} (mm/month)							
Grid1	0.71	-0.51	0.71	0.82	49.30	0.70	-29.20
Grid2	0.52	11.73	0.56	0.82	87.48	0.55	-39.50
Grid3	0.94	3.48	0.97	0.80	30.22	0.78	0.10
Grid4	1.20	1.40	1.21	0.83	33.78	0.62	22.60
Grid5	0.72	6.49	0.76	0.76	34.64	0.74	-16.30
Grid6	0.80	2.55	0.82	0.74	31.67	0.72	-14.70
$ET_{o\ OBS}$ vs $ET_{o\ REAN}$ (mm/day)							
Grid1	0.93	0.41	1.07	0.72	0.70	0.62	9.30
Grid2	0.73	0.84	0.96	0.76	0.77	0.75	2.90
Grid3	0.83	0.94	1.09	0.77	0.81	0.66	16.00
Grid4	0.65	1.13	0.92	0.80	0.87	0.77	-0.60
Grid5	0.80	1.26	1.14	0.78	0.96	0.57	22.00
Grid6	0.68	1.38	1.00	0.79	0.87	0.75	8.30

*b is the regression coefficient of a linear regression, a is the intercept of the linear regression, b_0 is the regression coefficient of a linear regression forced to the origin, R^2 is the coefficient of determination, RMSE is the Root Mean Square Error, EF is the efficiency of modelling, PBIAS is the Percent Bias. * indicates the same units as the variables.*

3.3 Comparing PDSI and SPI when computed from reanalysis products or observations

Fig. 2 shows the comparison between PDSI and SPI-9 obtained from the reanalysis data ($PDSI_{REAN}$, SPI-9_{REAN}) and the respective PDSI and SPI-9 computed with the observed data ($PDSI_{OBS}$, SPI-9_{OBS}) by comparing the frequency of each drought class. The different drought classifications relative to both indices were adopted. Results show that the frequency of extreme and severe drought events are much larger when PDSI was computed from reanalysis data. Only for Grid4 the frequency of severe events of $PDSI_{REAN}$ is lower. However, the frequency of drought events detected by SPI-9_{REAN} is closer to SPI-9_{OBS}. Extreme wet events are more frequent through the SPI-9_{OBS}, and extreme and severe events are more frequent through SPI-9_{REAN} although the difference is smaller than when comparing $PDSI_{REAN}$ with $PDSI_{OBS}$.

Considering the nature of the DI, the underestimation of precipitation and the overestimation of ET_o, results in Fig.3 are acceptable to analyze how PDSI and SPI changed with time and with the CP. Since PDSI combines precipitation and ET_o through a water balance, if precipitation is greatly underestimated and ET_o is overestimated, then drier, more frequent, events are expected. Differently, as the SPI is a probabilistic index that computes the deviation from average precipitation conditions, the underestimation of P_{REAN} should not affect the frequency of dry events detected as long as the reanalysis time series are able to describe the variability of observed precipitation, which was the case for precipitation (Table 1).

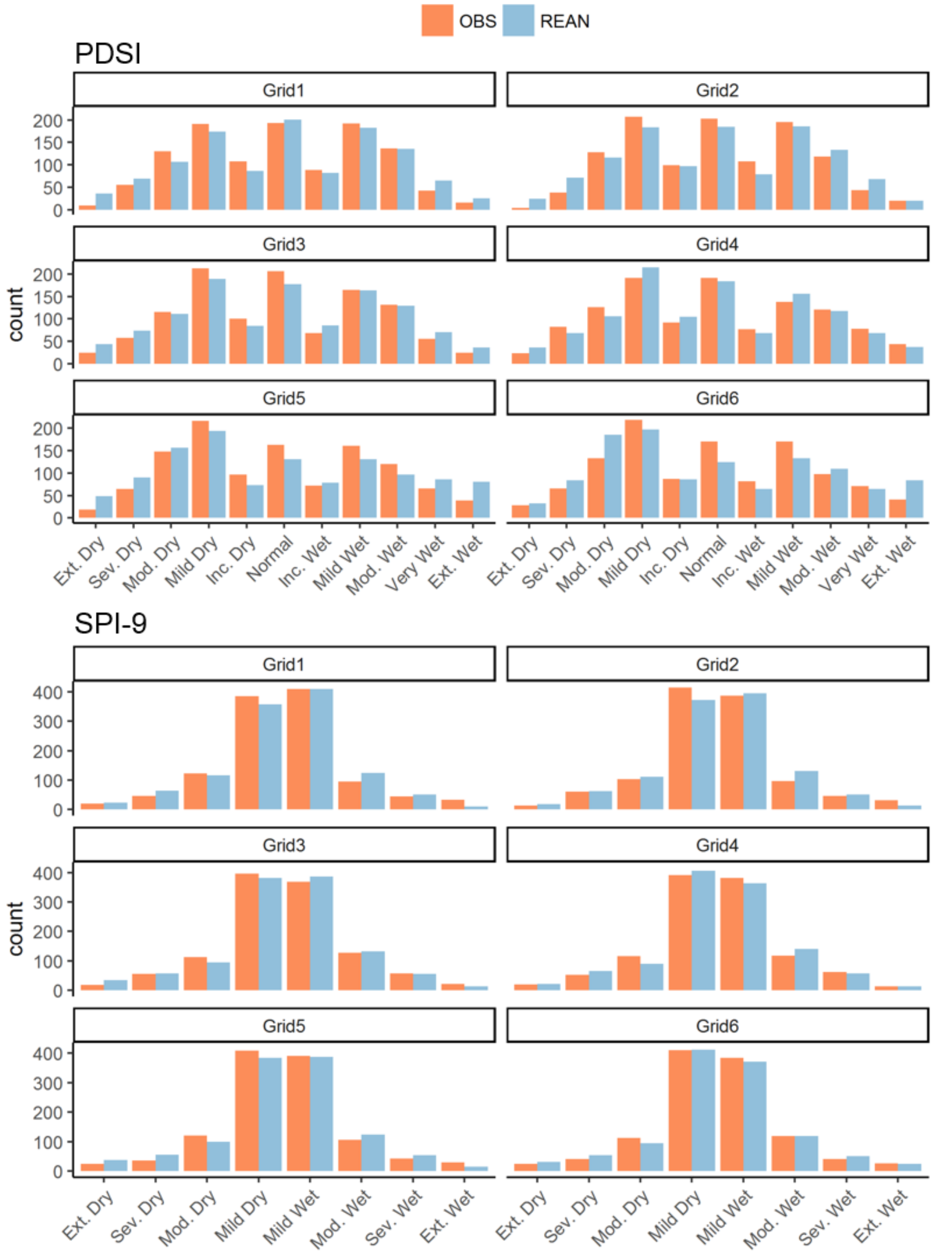

Figure 2. Comparison of the count of occurrences in each class of PDSI and SPI-9 computed reanalysis and observations (Ext. Dry: Extreme droughts; Sev. Dry: Severe droughts; Mod. Dry: Moderate droughts; Mild Dry: Mild droughts; Incip. Dry: Incipient drought; Incip. Wet: Incipiently wet; Mild Wet: Mildly wet; Mod. Wet: Moderately wet; Very Wet: Very wet; Ext. Wet: Extremely wet).

3.4 Analyzing the long-term variability of PDSI and SPI-9 and effects of the calibration period

To assess how the climate variability affect both PDSI and SPI-9, different CP periods were used to estimate the Gamma pdf parameters, for SPI-9, and the potential values of the water balance of the PDSI, using the 20th-century reanalysis data for the period 1851-2014.

Results show that despite no major changes occurred in the time variability of precipitation and ET_o in the entire period, the selection of the reference period is important. Results are coherent for all grid-points and to both PDSI and SPI; however in Table 3 only examples for Grid2 and Grid3 are shown. Focusing the analysis on the occurrence of extreme and severe events, there are clear differences between the PDSI time series calibrated for the five reference periods. The PDSI calibrated using the complete period (1851-2014) identified more extreme and severe drought events relative to calibration for the periods 1851-1891 and 1974-2014, and lesser number of extreme and severe wetness events than those identified when the PDSI was calibrated for those periods. In fact, the PDSI calibrated for 1974-2014 is the most different when compared to the other CP. Only 4 or 5 extreme dry events were identified in 164 years in Grid2 and Grid3, respectively, and 30 severe drought events were identified, which are much less than those identified for all other periods. The number of severe and extreme wet events increased significantly in this period in all grid-points when compared to the PDSI calibrated for the other periods. Similar results were found for SPI-9 for all grid-points. Lower occurrence of extreme and severe events were identified when the SPI-9 was calibrated for the period 1974-2014 and with the highest occurrence of extreme and severe wet events being identified for this CP as well. The highest occurrence of severe and extreme dry events occurred when both DI were calibrated using the wet periods 1892-1932 and 1933-1973 (Table 3) Although not fully comparable, these results agree with those reported by Paulo et al. (2016), highlighting the importance of the reference period selected for calibration.

Table 3. Count of occurrences in each class of PDSI and SPI-9 using different calibration periods for Grid2 and Grid3

Index	Calibration Period	Ext. Dry	Sev. Dry	Mod. Dry	Mild Dry	Inc. Dry	Normal	Inc. Wet	Mild Wet	Mod. Wet	Very Wet	Ext. Wet
PDSI												
Grid2	1851-2014	35	137	200	323	150	304	149	322	209	98	41
	1851-91	22	93	191	313	165	308	168	303	225	124	56
	1892-32	100	167	246	320	173	297	141	285	160	56	23
	1933-73	74	175	240	354	167	325	140	260	155	53	25
	1974-14	4	30	161	256	136	305	135	353	263	197	128
Grid3	1851-2014	68	137	207	324	143	270	137	281	218	127	56
	1851-1891	62	134	220	320	150	266	151	265	223	123	54
	1892-1932	124	165	236	328	126	287	131	239	205	86	41
	1933-1973	128	163	261	345	150	290	115	266	162	56	32
	1974-2014	5	45	143	261	97	255	137	305	293	207	220
		Ext. Dry	Sev. Dry	Mod. Dry	Mild Dry	Mild Wet	Mod. Wet	Very Wet	Ext. Wet			
SPI-9												
Grid2	1851-2014	35	104	203	593	703	207	90	25			
	1851-1891	21	62	179	617	757	212	87	25			
	1892-1932	150	147	233	491	610	173	99	57			
	1933-1973	93	154	232	615	637	149	61	19			
	1974-2014	13	35	119	561	779	264	128	61			
Grid3	1851-2014	44	100	173	638	688	205	75	37			
	1851-1891	23	72	177	659	741	196	62	30			
	1892-1932	134	119	231	590	540	191	101	54			
	1933-1973	91	144	220	628	617	157	63	40			
	1974-2014	12	35	112	564	759	283	124	71			

The time variability of PDSI and SPI-9 was further studied by identifying the main cycles for drought occurrence. A spectral analysis was applied to the time series of the September values of both SPI-9 and PDSI for all grid-points. The analysis was done using the September values because it is the last month of the hydrological year and with the SPI-9 the index value of September included all the precipitation that occurred that year. For PDSI the most relevant cycles identified for all grid-points were the 6.21 and 7.83 year cycles. Other cycles of 12 and 90 years were also present in all grid-points for PDSI. Results for SPI, show in general, shorter cycles of drought occurrence with cycles of 2.02, 3.91 and 6.21 years present in all grid-points. These results agree with previous studies (Moreira et al., 2015) in which the most frequency cycles found with SPI-12 were of 9.4 and 6.0 years, although cycles of 2.0 and 4.7 years were also identified. Like discussed in Moreira et al. (2015) the 6 year and 7.83 year cycle are likely influenced by the North Atlantic Oscillation (NAO) that influence winter precipitation in Portugal.

4. CONCLUSIONS

In the present study, the long-term variability of droughts was assessed with the PDSI and the SPI-9 using data derived from the 20th-century reanalysis products, with data from 1851 to 2014. The accuracy of reanalysis precipitation and PM-ET_o were compared against observations. The resulting drought indices computed using those variables were also compared with those computed from observations. Results showed that SPI-9_{REAN} relates well with SPI-9_{OBS} for all grid-points; in all cases the frequency of events in each class of the SPI-9_{REAN} is very close to those of SPI-9_{OBS}. $PDSI_{REAN}$ relates worst with $PDSI_{OBS}$ than referred for both SPI-9 because the frequency of extremely dry (wet) events identified with $PDSI_{REAN}$ is considerably larger (lower) then that identified by $PDSI_{OBS}$. This may be explained by the underestimation of P_{REAN} and the overestimation of $ET_{o\ REAN}$ resulting in less water availability when the water balance is performed, which leads to drier $PDSI_{REAN}$. With SPI-9, due to its probabilistic feature, the consistent underestimation of precipitation does not significantly affect its standardized values. Statistical downscaling techniques should be studied to correct the biases in precipitation and ET_o to improve the accuracy of the PDSI from reanalysis.

To study how the long-term variability precipitation and ET_o affect the DI, both indices were calibrated for 5 different periods. Results showed very distinct index values depending on the CP used. With the same patterns for all grid-points, when the DI were calibrated with the most recent period (1974-2014) the amount of severe or extreme droughts were the lowest when compared to the $PDSI_{REAN}$ and SPI-9_{REAN} computed for other CP; also, with this CP, the number of severe and extreme wet events were the highest. In contrast, if the CP selected was the period 1892-1932, the opposite occurred with a larger amount of dry events and fewer wet events detected. In general wetter (dryer) CP lead to an SPI biased towards drier (wetter) classes. These results showed the importance that the selection of the CP has to both PDSI and SPI-9. However, further studies are required to understand if the changes observed with $PDSI_{REAN}$ and SPI-9_{REAN} represent the reality, particularly after using an appropriate bias correction for P_{REAN} and $ET_{o\ REAN,}$ and which CP should be used for drought monitoring.

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