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Modification of the Palmer Drought Severity Index for Mediterranean environments: Model and application

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Abstract: This article describes a modification of the Palmer Drought Severity Index (PDSI) as adapted to Mediterranean conditions, resulting in a new index, the MedPDSI. It differs from the original PDSI because the olives crop, a typical Mediterranean perennial resistant to water stress, is assumed as drought reference crop aiming at the application of the soil water balance. The adopted approach modifies the soil water balance computation, with the actual evapotranspiration computed with the FAO-PM reference ET_o and a crop coefficient obtained from the FAO dual K_c approach, $K_c = K_{cb} + K_e$. The basal crop coefficient K_{cb} refers to transpiration and is parameterized at the month scale for a typical rainfed olives grove. The soil evaporation coefficient K_e is estimated every month as a function of soil evaporation, thus depending on monthly precipitation, evaporative atmospheric demand and the soil evaporation characteristics following FAO56. The basic computations of PDSI are kept and self-calibration is adopted. MedPDSI was tested for various soil types and locations across Portugal. Comparing results of the water balance with MedPDSI and PDSI, it is apparent a larger actual ET during the rainy months and smaller in the dry months with MedPDSI; coherently, runoff and percolation decrease. It results, however, relatively similar identification of drought and wetness periods, with the MedPDSI responding quicker to changes in precipitation.

Key words: PDSI, MedPDSI drought index, soil water balance, rain-fed olives crop, actual evapotranspiration

1. INTRODUCTION

Drought is a climatic event characterized by a persistent lower than average precipitation with an uncertain frequency, duration and severity resulting in diminished water resources availability. Several drought indices have been developed with the purpose of drought monitoring and drought severity evaluation.

The Palmer Drought Severity Index (Palmer, 1965) is widely used for drought monitoring and in studies on climate change. Precipitation, temperature and soil water holding capacity are required to compute the PDSI. Main limitations of the PDSI refer to the adoption of the Thornthwaite's potential evapotranspiration and the soil water balance modelling (Alley, 1984).

Considering limitations of the method and developments in the ET and soil water balance domains, an adaptation of the PDSI to Mediterranean conditions, the Mediterranean Palmer Drought Severity Index (MedPDSI) was firstly proposed by Pereira et al. (2007). The MedPDSI has been already compared positively with the PDSI, SPEI and SPI in Portugal (Paulo et al., 2012). The backbone of MedPDSI is the soil water balance applied to an olive orchard, by estimating separately soil evaporation and transpiration of the olive crop adopting the dual crop coefficient approach (Allen et al., 1998) modified for a monthly time scale. The objective of this study is to model MedPDSI adopting a self-calibration procedure and to assess its performance for various locations in mainland Portugal comparatively to PDSI.

2. MODIFICATION OF PDSI AND DEVELOPMENT OF THE MedPDSI

2.1 Palmer's formulation

The computation of the PDSI begins with a soil water balance described by (Palmer, 1965)

$$P = ET + RO + (R - L) \tag{1}$$

where P is precipitation, ET is evapotranspiration, RO is runoff, R is soil water recharge and L is soil water loss. The soil is divided in two layers: the surface layer has an available water holding capacity of 25 mm, the water holding capacity of the underlying layer depends on the soil characteristics. The potential evapotranspiration (PET) is computed by the Thornthwaite equation. The ET from the surface layer takes place at its potential rate. ET rate from the underlying layer is a linear function of the ratio between available soil moisture in this layer to water holding capacity of both layers. The water extraction from the underlying layer begins after the total depletion of the surface layer. The recharge of the underlying layer takes place after the surface layer is replenished. Runoff occurs when both layers reach field capacity. The potential terms PRO, PR, PL express a hypothetical maximum of RO, R and L. The precipitation climatically appropriate for existing conditions represents the amount of precipitation expected to maintain normal soil moisture level in a single month i, here denoted by $\hat{P}_i$ as

$$\hat{P}_i = \alpha_j PET_i + \beta_j PR_i + \gamma_j PRO_i - \delta_j PL_i \tag{2}$$

where the coefficients α_j, β_j, γ_j, δ_j are calculated for each month j as the ratio between the average of estimated and potential terms over a calibration period.

The moisture anomaly index z is obtained by

$$z = k_j (P_i - \hat{P}_i) \tag{3}$$

where k_j is the climatic characteristic for the month j, obtained by an equation using central United States data. The PDSI for month i, X_i, is then derived from z_i, and the PDSI of month i-1, X_{i-1}:

$$X_i = p X_{i-1} + q z_i = 0.897 X_{i-1} + z_i / 3 \tag{4}$$

The p and q are called duration factors and express the sensitivity of the index to precipitation. The values p = 0.897 and q = 1/3 were obtained by Palmer using cumulated z during the driest periods of various lengths in two locations. The computation of the PDSI requires the computation of three intermediate indices, X_1, X_2 and X_3 using Eq. 4, X_1/X_2 representing the severity of a wet/dry spell that is becoming established, X_3 the severity index for any wet/dry spell that has become established. The selection of the PDSI from those indices relies on complex operating rules and a backtracking procedure.

The self-calibration of the PDSI replaces k_j and p and q by values computed in each location from the historical climatic data. The self-calibration procedure initiates after having calculated *d* and follows several sequential steps to obtain the self-calibrated PDSI, sc-PDSI (Wells et al., 2004). The methods for defining the wettest and driest periods and the choice of time lengths to obtaining the duration factors are analysed by Dai (2011). The adjustment of the climatic characteristic and the duration factors to local climate conditions allows a better spatial comparability and reduces PDSI range; however the sc-PDSI still does not have a symmetric distribution.

2.2 MedPDSI: the new soil water balance

The modifications base upon considering a rainfed olive crop as water balance reference crop because it is a perennial crop well adapted to water stress and to the Mediterranean environments. The current model to compute MedPDSI is modified from that proposed by Pereira et al. (2007).

The water balance may be performed for a variety of soils. Presently, the soil type may be chosen from nine different soil types, according to texture, the average soil water holding characteristics and soil evaporation parameters as for the dual K_c approach (Allen et al., 1998; Rosa et al., 2012). The soil water balance considers the rooting depth of a mature olive grove and the sensitivity of the olive tree to the water stress. The actual ET (ET_a) is computed through the soil water balance. The counterpart potential term is the maximum/standard crop evapotranspiration $ET_c = K_c ET_o$ where K_c is obtained using the FAO56 dual K_c approach. Other computational procedures follow Palmer´s rules (Section 2.1) and self-calibration is also adopted for MedPDSI.

The monthly weather input data are precipitation (P) and reference evapotranspiration (ET_o), computed by the FAO56 Penman-Monteith equation (Allen et al., 1998). The generic equation of the soil water balance is:

$$\Delta ASW = \left(P - ET_a - R_{off} - D_p\right) \tag{5}$$

where ΔASW is the variation of the available soil water stored (ASW) in the root zone, R_{off} is surface runoff due to non-infiltrated precipitation, ET_a is actual crop evapotranspiration and D_p is deep percolation through the bottom of the root zone. The deep percolation is computed assuming that drainage from the root zone occurs immediately after excess precipitation (Doorenbos and Pruitt, 1977). $R_{off} = 0$ as daily data is required for its computation.

Water use and evapotranspiration of olive orchards has been often studied, recently adopting the dual K_c approach (e.g., Allen and Pereira, 2009; Cammallieri et al., 2014; Paço et al., 2015) thus partitioning ET into crop transpiration and evaporation from the soil. The crop coefficient is $K_c = K_{cb} + K_e$. The basal crop coefficient K_{cb} refers to transpiration and is parameterized at the month scale for a typical rain-fed olive grove with 30% ground cover based upon the referred studies. The resulting K_{cb} values are: 0.33 for the months of January to April and the autumn months of November and December, 0.28 for the summer months of June through September, and 0.30 for the transition months of May and October. For a rain-fed crop in a Mediterranean climate higher K_{cb} are expected when rain has refilled the soil and lower K_{cb} are observed during the dry summer months despite the atmospheric demand for evaporation is high. K_e is the soil evaporation coefficient, which was parameterized for every month based upon Paço et al. (2015) and simulations of the olive crop performed for various Portuguese locations using the SIMDualKc model (Rosa et al., 2012). It was therefore possible to establish the following equation

$$Ke_i = 0.2424 - 0.00131 ETo_i + 0.002875 P_i + 0.00126 P_{i-1} \tag{6}$$

with K_e restricted to $0 \leq K_e \leq (1.2\text{-}K_{cb})$ and depending upon ET_o, the precipitation of the current and of the previous month, respectively P_i and P_{i-1}. K_e is further corrected for the evaporative characteristics of the surface soil layer. Fig. 1 shows that K_e generally decrease with the aridity of the station because more humid locations have larger and more frequent replenishment of the soil evaporation layer than semi-arid ones, i.e., larger P_i and P_{i-1} (eq. 6), particularly when $ET_{o\,i}$ change little in space as it is the case for the considered weather stations.

The computation of ET_a depends on the depletion of the soil water: when depletion is smaller than the soil water depletion for no stress, p (p = 0.65 in this application), then no water stress occurs and actual crop ET equals the potential ET_c, i.e., $ET_a = ET_c$; differently, stress occurs when depletion exceeds p resulting $ET_a < ET_c$ (Allen *et al.*, 1998; Rosa et al., 2012). These stress conditions relate with the concepts of total and readily available soil water (TAW, RAW). TAW is the total amount of water that can be extracted by the vegetation from the root zone when the soil is at field capacity while RAW is the fraction of TAW that can be removed from the root zone without stress, i.e., RAW = p TAW. Therefore, adopting these concepts, droughts are differently identified for soils with large or small TAW and, consequently when also the rooting depth is larger or smaller. In this application, the root depth adopted for the olive trees is 1.5 m (Allen et al. 1998).

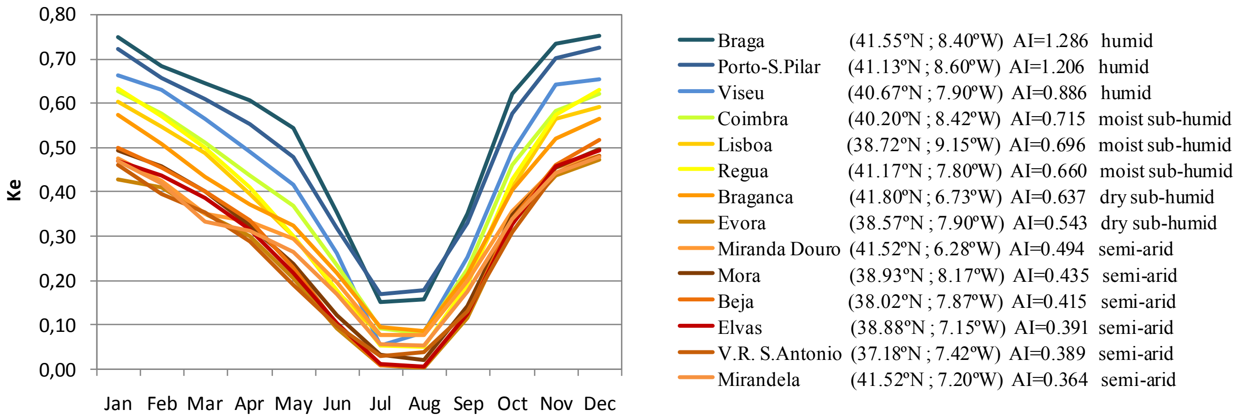


Figure 1. The monthly soil evaporation coefficient K_e averaged (1941-2006) at all locations

3. APPLICATION

3.1 Soil water balance: comparing MedPDSI with PDSI

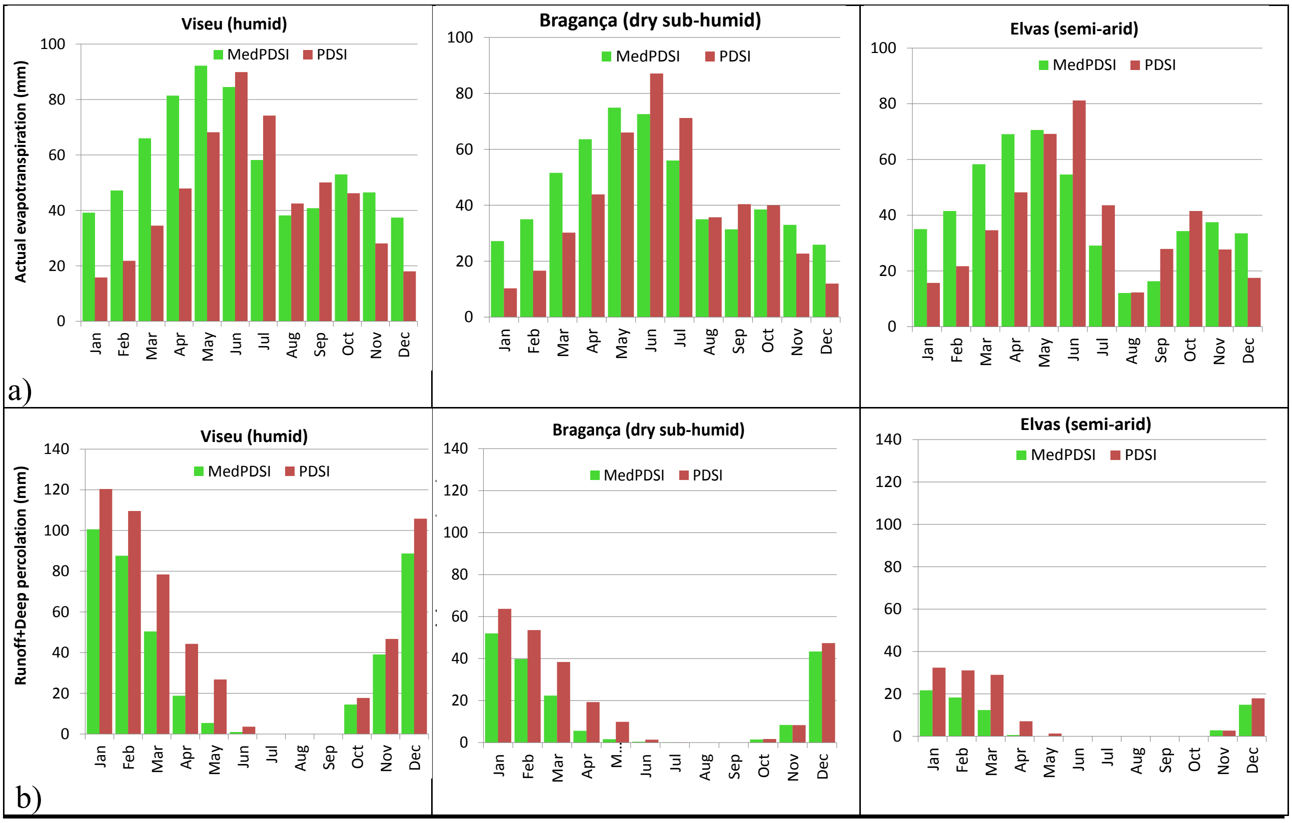
The drought indices PDSI and MedPDSI were computed in 14 weather stations across Portugal in the period 1941-2006. The aridity index computed as per UNEP shows that locations cover a good range of climates, from humid to semi-arid. The latitude and longitude of the weather stations and respective aridity indices are shown in Fig. 1.

The olives actual ET computed with MedPDSI and PDSI show non-negligible differences as depicted in Fig. 2a for three locations, Viseu having a humid climate, Bragança a dry sub-humid climate and Elvas a semi-arid climate. Adopting the Penman-Monteith ET_o and a simplified dual K_c approach, the soil water balance (SWB) used in MedPDSI leads to great changes in ET_a relative to the former Palmer's SWB. Results refer to a soil with TAW = 180 mm. For all locations, ET_a computed with MedPDSI increases relative to PDSI computations during the rainy and spring months, January to May, as well November and December. Contrarily, ET_a decreases during the dry months (Fig. 2c). This means that the SWB used in MedPDSI agrees with environmental conditions: actual ET is higher when more water is available in the soil, not only when the atmospheric demand is higher.

Changes in runoff and percolation (Fig. 2b) consistently indicate a decrease when computed with MedPDSI relative to PDSI. This may be explained by a likely better description of the soil and soil water dynamics with the approach used in MedPDSI, and to the fact that more soil water turns into ET_a. The ability of the model to perform in both humid and semi-arid conditions is demonstrated through the contrasting results relative to Viseu, Bragança and Elvas.

3.2 Drought identification by the PDSI and MedPDSI

The time variability of MedPDSI and PDSI is concordant for all locations. The time series of both indices and its calibrated variants (Fig. 3) are in agreement as shown for Viseu, Bragança and Elvas. The sc-MedPDSI in Viseu and Elvas reaches negative values before the sc-PDSI. For all stations (Table 1) the frequencies of the various drought and wetness classes show some discrepancies when comparing classic and self-calibrated MedPDSI with PDSI. The adoption of self-calibration tends to equilibrate the frequency of the various wet and dry classes, mainly in the case of sc-MedPDSI.



c) Stations	MedPDSI ET_a Nov-May (mm)	PDSI ET_a Nov-May (mm)	Difference (%)	MedPDSI $R_{off}+D_P$ Jan-Dec (mm)	PDSI $R_{off}+D_P$ Jan-Dec (mm)	Difference (%)
Braga	457.8	263.9	73%	664.9	844.2	-21%
Porto-Serra do Pilar	411.4	274.7	50%	493.9	604.0	-18%
Viseu	409.9	234.3	75%	390.6	532.0	-27%
Coimbra/Bencanta	421.3	274.2	54%	228.8	335.4	-32%
Lisboa (Geofisico)	341.4	286.9	19%	205.9	231.4	-11%
Regua	405.2	256.6	58%	251.6	348.7	-28%
Braganca	311.2	201.7	54%	173.2	240.6	-28%
Evora	320.9	247.7	30%	136.5	170.9	-20%
Miranda do Douro	283.5	195.3	45%	82.0	122.9	-33%
Mora	340.1	243.2	40%	94.1	145.5	-35%
Beja	348.7	245.1	42%	80.4	132.3	-39%
Mirandela	286.4	208.2	38%	38.1	59.4	-36%
Elvas	345.5	234.6	47%	70.7	121.5	-42%
Vila Real de S. Antonio	323.2	256.6	26%	51.7	77.9	-34%

Figure 2. Comparing the monthly averages (1941-2006) of (a) actual evapotranspiration for Viseu, Bragança and Elvas with the MedPDSI and the PDSI; (b) runoff and percolation estimated for the same locations and using the same indices; (c) computed differences for ET_a and $R_{off}+D_p$ for all studied locations.

4. CONCLUSIONS

The proposed drought index MedPDSI has been successfully developed considering the soil water balance of the olive crop and using an adaptation of the dual K_c approach. Monthly K_{cb} values were selected and K_e is determined for every month as a function of ET_o and precipitation of the current and past month. The soil characteristics are defined by the user, which determine both TAW and soil evaporative conditions. The adoption of the new SWB approach led to larger ET_a computed with MedPDSI than with PDSI during the rainy months, thus when more soil water is available. Contrarily, since with MedPDSI more water is used as ET_a, it results that the non-used precipitation, runoff and percolation, are smaller than for PDSI.

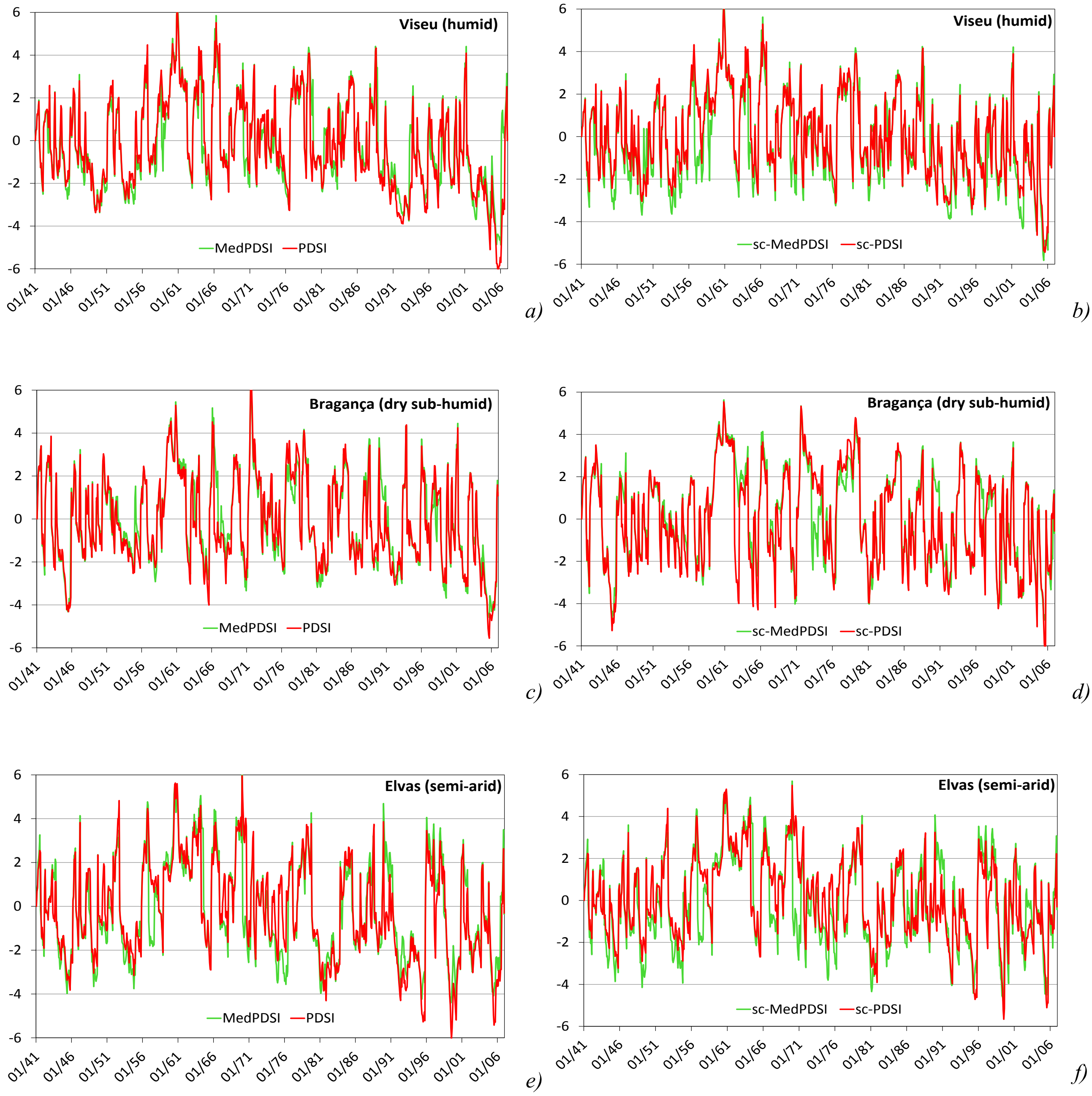


Figure 3. Time variability (1941-2006) of MedPDSI and PDSI (a, c, e) and self-calibrated MedPDSI and PDSI (b, d, f) in Viseu (a, b), Bragança (c, d) and Elvas (e, f)

The self-calibration for dry and wet periods reduced the asymmetry and balanced the frequency of mild/moderate dry and wet categories. Results from comparing MedPDSI and PDSI through the entire period of records led to conclude that both indices behave similarly in terms of time variability, but the sc-MedPDSI identified more frequently moderate, severe and extreme droughts than the sc-PDSI. This may indicate that the SWB performed with MedPDSI is well linked to the water supply-demand and is likely more realistic that PDSI.

Table 1. Average frequency (%) of drought/wet classes

Class		MedPDSI	PDSI	sc-MedPDSI	sc-PDSI
Average of all locations					
Dry	Extreme	1.5	2.8	2.0	2.2
	Severe	5.5	5.4	6.6	4.4
	Moderate	13.6	11.8	11.7	10.2
	Mild	37.9	37.2	29.6	33.5
Wet	Mild	22.8	23.1	29.7	29.2
	Moderate	10.7	11.2	11.6	11.7
	Severe	5.4	5.8	6.6	6.9
	Extreme	2.6	2.6	2.3	2.0
Average of the humid locations					
Dry	Extreme	0.5	0.8	1.9	3.3
	Severe	3.3	5.4	8.0	6.4
	Moderate	14.8	12.2	12.1	10.6
	Mild	41.6	40.0	27.6	30.3
Wet	Mild	24.5	24.6	31.9	31.8
	Moderate	8.5	10.2	10.8	10.4
	Severe	4.4	4.6	5.1	5.2
	Extreme	2.4	2.2	2.5	2.0
Average of the semi-arid locations					
Dry	Extreme	2.0	3.9	1.9	1.8
	Severe	7.0	6.3	6.3	3.1
	Moderate	13.7	11.1	10.8	9.3
	Mild	35.1	34.6	29.6	34.8
Wet	Mild	21.9	23.9	29.5	29.6
	Moderate	11.3	11.1	12.3	12.3
	Severe	5.9	6.1	7.2	7.0
	Extreme	3.1	3.0	2.4	2.0

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