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Global characterization of the varying responses of the Standardized Evapotranspiration Index (SPEI) to atmospheric evaporative demand (AED)

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Abstract. The Standardized Precipitation Evapotranspiration Index (SPEI) is one of the well-established drought metrics worldwide. It is simply computed using precipitation and atmospheric evaporative demand (AED) data. Although AED is considered a key driver of drought variability worldwide, it could have less impact on drought in specific regions and for particular times as a function of the magnitude of precipitation. Specifically, the influence of the AED might overestimate drought severity during both normal and humid periods, resulting in "false alarms" about drought impacts on physical and human environments. Here, we provided a global characterization of the sensitivity of the SPEI to changes of the AED. Results

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demonstrate that the contribution of AED to drought severity is largely impacted by the spatial and temporal variability of precipitation. Specifically, the impact of AED on drought severity was more pronounced during periods of low precipitation, compared to wet periods. Interestingly, drought severity in humid regions (as revealed by SPEI) also showed low sensitivity to AED under drier conditions. These results highlight the skill of SPEI in identifying the role of AED in drought evolution, especially in arid and semi-arid regions whose climate is characterized typically by low precipitation. This advantage was also evident for humid environments, where SPEI did not overestimate drought severity due to the increased AED. These findings highlight the broader applicability of SPEI to accurately characterize drought severity worldwide.

Key-words: Drought severity, climate change, soil moisture, SPEI, Atmospheric evaporative demand.

1. Introduction

Drought is a complex natural hazard, which is impacted by a wide variety of climatic variables. Accordingly, it is important to unravel the contribution of these different drivers and assess their role in drought severity (Mukherjee et al., 2018; S M Vicente-Serrano et al., 2020). This assessment has strong implications for detecting trends of drought severity in both current and future climates. When interpreting drought trends using the Standardized Precipitation Index (SPI) (Mckee et al., 1993), which employed precipitation data alone, there is often a low degree of uncertainty in evaluating drought trends in the present climate and future scenarios, as precipitation deficit is usually directly proportional to more severe and long lasting drought events. Nevertheless, precipitation could not be seen as the only variable impacting drought evolution, especially under the current global warming conditions and even more for future climate change scenarios. Due to air temperature rise, there is a stronger atmospheric vapor pressure deficit (W. Yuan et al., 2019). In the same context, relative humidity witnesses a decreasing trend over the majority of the continental areas worldwide (Willett et al., 2014), which is likely to be accelerated in the future, as suggested by climate model outputs (M. Byrne & O'Gorman, 2013; M. P. Byrne & O'Gorman, 2018). This situation will reinforce the atmospheric evaporative demand (AED) and thus it could increase drought severity (S M Vicente-Serrano et al., 2020).

The AED intensification during dry periods can increase levels of vegetation stress (Allen et al., 2015; Hartmann et al., 2018; A.P. Williams et al., 2013), higher evaporation rates from soil (Teuling et al., 2013) and water bodies (Friedrich et al., 2018), and accelerate hydrological drought downstream. Some drought indices like the Palmer Drought Severity Index (PDSI) (Palmer, 1965), the Reconnaissance drought index (RDI) (Tsakiris et al., 2007), the Standardized Moisture Anomaly Index (SZI) (B. Zhang, AghaKouchak, et al., 2019; B. Zhang, Xia, et al., 2019), the Standard Palmer Drought Index (SPDI) (Ma et al., 2014), and the Standardized Precipitation Evapotranspiration Index (SPEI) (Beguería et al., 2014; S.M. Vicente-Serrano et al., 2010) take into account AED when quantifying drought severity.

Some studies have suggested that there is some degree of uncertainty in quantifying drought severity using climate drought indices that account for the role of AED in their formulations (Berg & Sheffield, 2018; Cook et al., 2014; Greve et al., 2019; Scheff, 2018; Yang et al., 2019). Overall, the debate on the role of AED on drought severity (B. Cook et al., 2018; Dai et al., 2018; Greve et al., 2019) originates mainly from the notion that the role of AED is complex, depending largely on the drought type (e.g. meteorological, hydrological, environmental) and prevailing climatic conditions (S M Vicente-Serrano et al., 2020).

Some studies argue that AED is not a good metric of actual evapotranspiration (ET) because AED exceeds ET particularly in arid regions, leading to an overestimation of soil drying (Berg & Sheffield, 2018; Benjamin I Cook et al., 2014). While this assumption seems to be feasible, the inclusion of AED in climate drought indices cannot be introduced as a substitute of ET. Rather, irrespective of ET rates, accounting for the role of AED in drought metrics has a strong physical meaning with real implications in the intensification of hydrological, agricultural and environmental droughts (S M Vicente-Serrano et al., 2020). In the same context, some studies suggest that AED could not be seen as a good metric of plant water demand. These studies attributed this feedback to the role of the atmospheric CO_2 fertilization (Abigail L S Swann, 2018) and the role of vapor pressure deficit on stomata conductance, which can diminish plant water demand, even with high AED (Konings et al., 2017; Miralles et al., 2019). As such, it is expected that the atmospheric CO_2 fertilization would increase plant water use efficiency (Milly & Dunne, 2016; Roderick et al., 2015; A.L.S. Swann et al., 2016), alleviate plant water demand (Abigail L S Swann, 2018), and reduce the stress corresponding to hydrological deficits (Greve et al., 2019). However, the impact of atmospheric CO_2 fertilization is still uncertain (Brodribb et al., 2020; B. Cook et al., 2018; S M Vicente-Serrano et al., 2020). An important aspect is that the role of atmospheric CO_2 could be negligible during low precipitation periods (Menezes-Silva et al., 2019; Morgan et al., 2004; Z. Xu et al., 2016), making environmental and agricultural drought aggravated by any increase in AED (Allen et al., 2015; McDowell et al., 2016; McDowell & Allen, 2015). In addition, AED could largely reduce surface water resources due to reinforced land evaporation (B I Cook et al., 2019; Zhang et al., 2018). Also, vegetation changes may increase water consumption, especially in locations characterized by denser coverage, higher leaf area index and longer vegetation active periods (Frank et al., 2015; J.S. Mankin et al., 2018; Justin S Mankin et al., 2019).

There are also important statistical issues that should be carefully considered when interpreting drought changes associated with AED. These concerns are mostly related to how drought metrics are calculated (S. M. M. Vicente-Serrano et al., 2019). Overall, the different assumptions about the role of AED in drought severity, as revealed by climate drought metrics, are still questionable and deserve much more attention for better interpretation and understanding of drought severity.

In the past decade, SPEI has been one of the most widely used drought metrics worldwide. It has been used for different applications, including drought risk assessment (e.g. Domínguez-Castro et al. 2019; Blauhut et al. 2015), analysis of drought evolution (e.g. Spinoni et al. 2014; Chen and Sun 2015; Spinoni et al. 2019a), assessment of drought impacts in different socioeconomic (e.g. Bachmair et al. 2016, 2015; Leng and Hall 2019; Ribeiro et al. 2019; Von Uexkull et al. 2016; Zampieri et al. 2017; Gu et al. 2020), hydrological (e.g. Barker et al. 2016; Peña-Gallardo et al. 2019) and environmental systems (e.g. Babst et al. 2019; Mitchell et al. 2014; Zimmermann et al. 2015; Knapp et al. 2015; Slette et al. 2019; Fang et al. 2019; Bachmair et al. 2018), and characterization of drought in future scenarios (e.g. Dewes et al. 2017; Chen and Sun 2017; Naumann et al. 2018; Gu et al. 2020; Spinoni et al. 2019b).

A key aspect of SPEI formulation is that it responds equally to the role of precipitation and AED (Sergio M. Vicente-Serrano et al., 2015), making it a suitable metric to assess the response of drought severity to AED changes in regions with different climate characteristics. Based on this index, Vicente-Serrano et al. (2015, 2020a) indicated that in general precipitation showed more impact on drought evolution than AED at the global scale. The only exception was found for water limited regions, where AED may be more relevant in defining SPEI. It is suggested that the role of AED in hydrological and environmental drought severity is less significant during humid conditions and more pronounced during dry periods characterized by low precipitation and soil moisture deficit (S M Vicente-Serrano et al., 2020). Albeit with these earlier attempts to explore the response of drought severity to AED, a comprehensive assessment of the sensitivity of SPEI to changes in AED from a temporal perspective is still lacking and worth investigation. Such an assessment is important to determine whether drought severity, as revealed by SPEI, can be overestimated due to the possible role of AED. This assessment matters to both arid and humid regions worldwide to evaluate the suitability of SPEI to reliably capture the influence of AED on drought severity. A high sensitivity of this index to AED, especially during wet periods, may make the use of this index less robust for assessing drought severity.

The overall aims of this study are (i) to provide a global characterization of the sensitivity of SPEI to AED changes under different precipitation magnitudes, and (ii) to define the regions and periods in which this sensitivity is much stronger due to changes in precipitation intensities. Hereinafter, the terms "sensitivity of SPEI to AED" refers to the relative contribution of AED to the variability of SPEI.

2. Material and methods

Data of monthly precipitation and potential evapotranspiration (as a metric of AED) were retrieved from the Climate Research Unit (CRU) dataset CRU TS v. 3.26 (Harris et al., 2014), at a spatial resolution of 0.5º for the period 1901-2017. To guarantee an adequate spatial representation of the global main precipitation regimes, our analysis was restricted to the global land areas between 65ºN and 65ºS. From a practical perspective, calculating drought indices in desert regions is meaningless (Wu et al., 2007), but we included these regions to establish a wider range of validation of the obtained results. .

Climate balance (D), defined as the difference between precipitation and AED (P-AED), is standardized to obtain SPEI. In order to assess the sensitivity of SPEI to AED during different periods of the year, here the climate balance was calculated at three different time scales: monthly, seasonal and annual. Herein, SPEI at 1-month timescale was computed to characterize drought at monthly timescale. Also, SPEI at 3-month timescale was quantified for the months of February, May, August and November to account for drought in winter, spring, summer and autumn, respectively. Similarly, SPEI at 12-month timescale for December was considered as representative of annual changes in drought.

The role of AED in climate balance variability was assessed following the approach of Hobbins et al. (2012). Nonetheless, as our research focuses on a different variable, we adapted this approach to evaluate the contribution of AED and Precipitation (P) to the variability of the climate balance (D):

$$D = P - AED \qquad \text{Eq. 1}$$

The variability of D can be expressed as,

$$\sigma_D^2 \approx J^T C \, J \qquad \text{Eq. 2}$$

where J is the Jacobian matrix, with the two partial derivatives of D, and C is the variance-covariance matrix

$$J^T = \begin{bmatrix} \frac{\partial D}{\partial P} & \frac{\partial D}{\partial AED} \end{bmatrix} \qquad \text{Eq. 3}$$

$$C = \begin{bmatrix} \sigma_P^2 & \sigma_{P,AED} \\ \sigma_{AED,P} & \sigma_{AED}^2 \end{bmatrix} \qquad \text{Eq. 4}$$

Thus,

$$\sigma_D^2 \approx \frac{\partial D^2}{\partial P} \sigma_P^2 + \frac{\partial D}{\partial P} \frac{\partial D}{\partial AED} \sigma_{P,AED} + \\ + \frac{\partial D^2}{\partial AED} \sigma_{AED}^2 + \frac{\partial D}{\partial AED} \frac{\partial D}{\partial P} \sigma_{AED,P} \qquad \text{Eq. 5}$$

In order to quantify the contribution of each variable (i.e. P and AED) to the variability of climate balance (D), we split this expression into two parts, where B_{P} represents the contribution of P, while B_{AED} denotes the contribution of AED.

$$B_P = \frac{\partial D^2}{\partial P}\,\sigma_P^2 + \frac{\partial D}{\partial P}\,\frac{\partial D}{\partial AED}\,\sigma_{P,AED} \qquad \text{Eq. 6}$$

$$B_{AED} = \frac{\partial D^2}{\partial AED}\,\sigma_{AED}^2 + \frac{\partial D}{\partial AED}\,\frac{\partial D}{\partial P}\,\sigma_{AED,P} \qquad \text{Eq. 7}$$

As D is only a subtraction, the partial derivatives are easy to obtain.

$$\frac{\partial D}{\partial P} = 1 \text{ and } \frac{\partial D}{\partial AED} = -1 \qquad \text{Eq. 8}$$

Hence,

$$B_P = \sigma_P^2 - \sigma_{P,AED} \qquad \text{Eq. 9}$$

$$B_{AED} = \sigma_{AED}^2 - \sigma_{AED,P} \qquad \text{Eq. 10}$$

To allow the direct comparison between the obtained results for different sites and timescales, we computed the relative values of B_{AED} (Eq,11). Following this procedure, our results were independent of the absolute values of the variance, which are expected to vary amongst sites and timescales.

$$\beta_{AED} = 100\,\frac{|B_P|}{|B_P| + |B_{AED}|} \qquad \text{Eq. 11}$$

SPEI is based on standardization of D. Indeed, the standardization process changes the variance. However, our preference was to quantify the relative contribution of AED to the variability of D (i.e. β_{AED}). This also provides a metric of the relative contribution of AED to the variability of SPEI..

Herein, it is noteworthy indicating that our methodology was applied independently to the monthly, seasonal and annual series. However, all precipitation and AED series were detrended prior to making the analysis to avoid any possible effects of trends presented in the series (via their impact on variance) on the results.

We analyzed the sensitivity of the SPEI considering different precipitation conditions. First, we applied the sensitivity analysis to the complete series (1901-2017). However, to identify whether this sensitivity can be changeable as a function of precipitation dryness, we also calculated the sensitivity, but for sampled years, seasons and months. These samples were selected using precipitation thresholds of 10th, 25th and 50th centiles. These centiles refer to periods with different drying conditions.

3. Results and discussion

3.1. Local sensitivity

Figure 1 illustrates representative examples of the sensitivity of SPEI to AED in four regions with different climatic conditions. Results are presented at the monthly, seasonal and annual scales. This analysis considered SPEI at 1-, 3-, and 12-month timescales as representative of monthly, seasonal and annual variability of drought, respectively. Also, differences in the sensitivity of SPEI to AED, as a function of precipitation magnitude, are presented at the monthly, seasonal and annual scales. Overall, results demonstrate that in the Sahel SPEI is completely (100%) sensitive to AED during the long dry season (November-March). This suggests that the interannual variability of SPEI during this period of the year is determined exclusively by AED. During the rainy season (April-October), the sensitivity of SPEI to AED decreases, reaching its lowest values (< 20%) during months of higher precipitation (i.e. July and August). This implies that the interannual variability of SPEI during the rainy season is mainly driven by precipitation variability. Notably, the importance of the AED in drought evolution increases during dry years. For example, the sensitivity of SPEI to AED in July and August during the years below 50th centile of precipitation exceeded 20% and during the years below 10th of precipitation; the sensitivity of the SPEI was around 40%.

Figure 1 reveals that there exists a strong variability in the sensitivity of SPEI to AED in response to the dominant climate characteristics. For example, in the humid equatorial regions (Congo), the sensitivity of SPEI to AED is practically negligible at the annual and seasonal scales. Exceptionally, the sensitivity was higher than 20% during the sesons below the 10th centile of precipitation, suggesting that the temporal variability of drought in these regions depends mainly on precipitation variability. However, AED seems to have a considerable role in drought variability (as revealed by SPEI values) during the most driest months (mainly summertime). In the same context, the sensitivity of SPEI to AED is expected to be low in temperate humid regions (as represented by Scotland). The sensitivity of SPEI to AED in this region was small considering the complete series (1901-2017) at the monthly, seasonal, and annual scales. In Scotland, the contribution of AED to SPEI variability was 5% at the annual scale and around 10% during summer months (June-August). Similarly, the sensitivity was also small (20%) during the years below 10th of precipitation. AED showed stronger influence on SPEI only during the very dry summers. In the semiarid northeastern Spain, the sensitivity of SPEI to AED was below 20% at the annual scale. Again, the sensitivity increased during summertime, approaching 100% during the years below 10th of precipitation. This extreme sensitivity might be expected given that precipitation amounts are very low during dry years, making AED a dominant factor controlling D. Thus, the sensitivity of SPEI to AED was more important during these dry years and typically more relevant during the driest and warmest season of the year (summer).

An inspection of Figure 1 suggests that SPEI is more sensitive to AED variability during periods of low precipitation, which is coherent with what is desired from a drought index like SPEI. Indeed, the influence of AED on hydrological and environmental systems is more relevant during low precipitation periods (S M Vicente-Serrano et al., 2020). However, in general, the temporal variability of SPEI is mostly driven by precipitation, which is undoubtedly the main controller of drought variability. Our results noted remarkable spatial differences in the sensitivity of SPEI to AED, which are largely driven by the magnitude and variability of precipitation and climate seasonality. These spatial differences are well identified at the global scale, being modulated by precipitation anomalies.

3.2. Global sensitivity

Figure 2 depicts the global spatial distribution of the sensitivity of SPEI to AED at the 12-month (annual) timescale. Considering the complete series, only the driest areas of the world exhibited a remarkable sensitivity, close to 100% of sensitivity in deserts. This sensitivity was lower (50-100%) in the neighboring dry areas. In the rest of the world, the sensitivity of SPEI to AED was much smaller. Notably, sensitivity of the SPEI to the AED was close to 0% over the majority of South America, Africa, South Asia, and eastern portions of North America. These spatial patterns inform that SPEI values were mainly driven by precipitation and, apart from very dry regions worldwide, SPEI showed low sensitivity to AED. Also, this stresses that SPEI is sensitive to AED only when precipitation amounts decline substantially. The percentage of the world areas showing a high sensitivity of SPEI to AED increased during dry years (Figure 3). For example, an inspection of the 50th centile reveals that a smaller percentage of world areas exhibiting a considerable sensitivity of SPEI to AED, compared to the 25th and the 10th centiles of the dry years. Only when considering the 10th and 25th centiles of precipitation, a noticeable influence of AED on SPEI was identified over large areas of South America, South Africa, central Asia, Australia, Europe and North America. At the monthly and seasonal scales, important spatial differences were noted (Supplementary Figures 1 to 16), which can be directly linked to climate seasonality. However, results stress that the spatial patterns of SPEI sensitivity to AED depend largely on precipitation amount, irrespective of SPEI time scale and the period of the year (Supplementary Figures 17 and 18). Overall, the sensitivity to AED increases during low precipitation periods, although the world area showing high sensitivity increased (mainly driven by higher AED) during boreal summers.

Here, we should stress that it cannot be inferred that the general drought conditions in these areas are only driven by AED, as this is clearly demonstrated by the negligible sensitivity of SPEI to AED in the complete series. Rather, drought is mostly driven by precipitation variability. Nevertheless, it is suggested that AED effect is more relevant during years with low precipitation. Therefore, the severity of drought, as suggested by SPEI, would be accentuated or diminished during low precipitation years following the behavior of AED. Simply, apart from world deserts, the interannual variability of SPEI is driven by precipitation variability. However, AED can be significantly relevant to drought quantification during years of low precipitation. This is strongly coherent with what would be desirable in a metric that tries to account for the effect of AED on drought severity. This is typically the case for SPEI, given that our global assessment confirms that the role of AED is only relevant during periods of low precipitation and/or limited soil moisture. During humid periods, an increase of the aerodynamic (e.g. air temperature) and radiative (i.e. solar radiation) components of AED is favorable for photosynthetic activity and growth (Niu et al., 2008; White et al., 1999). As such, any increase of the AED during these periods would not expect to increase vegetation stress in natural ecosystems and crops. Rather, an increase of AED could have negative influences on water resources through direct evaporation from lakes and reservoirs (Friedrich et al., 2018). However, this feedback not be expected to be relevant in absence of climatic conditions favoring for meteorological and hydrological droughts. In contrast, during dry periods, the enhanced AED could reinforce water stress in natural plants and cultivations (Allen et al., 2010, 2015; Hartmann et al., 2018; McDowell et al., 2016; A.P. Williams et al., 2013). Similarly, it would also increase the severity of hydrological droughts through accelerating evaporation from soil moisture (Teuling et al., 2013), water courses, reservoirs and lakes (Martínez-

Granados et al., 2011) or irrigated lands (S.M. Vicente-Serrano et al., 2017). Therefore, according to the results obtained here, SPEI is highly suitable for identifying enhanced drought severity associated with increased AED during dry periods. This important aspect highlights the potential of using this drought metric to assess environmental and hydrological impacts of drought in different regions worldwide, irrespective of the dominant climatic conditions.

3.3. The role of mean precipitation

In addition to differences in SPEI sensitivity to AED, as driven by the precipitation amount, this study also suggests coherent spatial patterns considering the average precipitation amount (refer to Figure 1). Specifically, the sensitivity of SPEI to AED was much lower in humid regions than in dry regions, irrespective of of the investigated sample (i.e. either from the complete series or series of precipitation below 10th, 25th and 50th percentiles) and the temporal scale (i.e. monthly, seasonal, and annual). In this context, although some regions exhibited an increase of the sensitivity of SPEI to AED during periods of low precipitation, other regions showed less sensitivity of of SPEI to AED, even during low precipitation periods. Again, this informs that the sensitivity of SPEI to AED is driven largely by climatology of precipitation, regardless of SPEI timescale (Figure 4, Figures S19 to S22). When considering the entire series, we found an exponential relationship between the sensitivity of SPEI to AED and mean precipitation. This exponential relationship was also found for the periods of low precipitation. Interestingly, the frequency of regions that showed a low sensitivity of SPEI to AED in very humid regions (> 3000 mm year^{-1}) did not change substantially when considering the years of low precipitation. In areas characterized by sub-humid to very arid conditions (0 to 800 mm year^{-1}), we noted an increase in the frequency of areas showing high sensitivity of SPEI to AED during low precipitation years. This implied that the majority of these regions exhibited a clear increase in the sensitivity of SPEI to AED during low precipitation years. Focusing on the the driest years (10th centile), most of these regions showed sensitivities higher than 50%. This pattern is clearly evident when exploring the sensitivity of SPEI to AED, as a function of different precipitation averages (Figure 5 and Figures S23 to S38).

3.4. General implications

In general, our analysis based on long-term climate data of precipitation and AED revealed that the sensitivity of SPEI to AED showed a strong temporal coherence. In particular, SPEI was only sensible to AED during low precipitation periods, in which an increase of AED would undoubtedly intensify the severity of hydrological, agricultural and environmental droughts. Interestingly, this behavior is not spatially homogeneous, as dry to sub-humid regions, which are characterized by frequent and even critical water deficits, experienced high sensitivity to AED during low precipitation periods. In contrast, the most humid regions of the world showed weak sensitivity to AED even under low precipitation conditions. High precipitation amounts in these humid regions can modulate the impacts of the interannual variability of AED on drought severity, although some influence can be found in dry years. This was clearly evident for the Congo site, where AED showed a relatively moderate role (15-35%) during dry seasons with very low precipitation (Figure 1). These regions can still be triggered by extreme droughts, mainly driven by low precipitation [e.g., the Amazon (J.A. Marengo & Espinoza, 2016; Jose A. Marengo et al., 2011), Equatorial Africa (Sorí et al., 2017) or Indonesia (Ummenhofer et al., 2013; Wooster et al., 2012)]. In the meantime, AED could reinforce vegetation stress and water deficits during these anomalous dry events.

The role of AED in drought severity (as revealed by SPEI) is robust, confirming that drought severity cannot be impacted by any possible overestimation due to the role of AED. This role is obviously evident during low precipitation periods (S M Vicente-Serrano et al., 2020). Any uncertainties originating from the overestimation of AED contribution on SPEI could only be raised during high precipitation periods (S M Vicente-Serrano et al., 2020). Nevertheless, this possible effect is meaningless, given that the role of AED is practically negligible during non-dry periods.

Small changes in the values drought indices accounting for AED in their formulations can be expected for the long term (Jonathan Spinoni, Barbosa, De Jager, et al., 2019), mostly as a consequence of the global weak changes in precipitation during the last decades (Orlowsky & Seneviratne, 2013; J. Spinoni et al., 2014). Nevertheless, impact-based studies suggest that when precipitation deficits are recorded, an increased AED contributes to drought intensification. This was perfectly described by Breshears et al. (2005) who introduced for the first time the term “global-change-type drought” to refer to reinforced drought conditions as a consequence of global warming. This concept is consistent with what dominantly observed:, mainly the global increase of AED due to recent warming processes (S M Vicente-Serrano et al., 2020). Therefore, although we cannot affirm with confidence that AED affects drought trends quantified by climate indices like SPEI, we still believe that dryness can be reinforced by enhanced AED when precipitation deficits occur. This has been evident for many regions worldwide, including Europe in 2003 (García-Herrera et al., 2010) and 2017 (García-Herrera et al., 2019), and southern portions of North America over the past two decades (Udall & Overpeck, 2017; Xiao et al., 2018). Moreover, this would not be inconsistent with the general evolution of mean vegetation and hydrological metrics over the last decades worldwide (Scheff, 2018). Rather, it would be consistent with enhanced forest decay (Carnicer et al., 2011) and mortality episodes in response to severe drought events reinforced by higher AED (Allen et al., 2015; Anderegg et al., 2013). Herein, it should be stressed that the role of AED on intensification of drought would be independent of the different thermodynamic and dynamic mechanisms that drive AED variability (see further details in Vicente-Serrano et al. 2020).

Studies based on climate change projections reveal a reinforcement of future dryness conditions, as revealed by SPEI (Naumann et al., 2018; Jonathan Spinoni, Barbosa, Bucchignani, et al., 2019; S.M. Vicente-Serrano et al., 2020b). This trend would be stronger in arid and semiarid regions. Cook et al. (2014) suggested that this could be a possible sign of dryness overestimation caused by SPEI formulation, which continues responding to changes in AED although ET supply is limited. Nevertheless, we must state here that AED is not included in SPEI as a substitute of ET (Beguería et al., 2014). Rather, it is included as a more comprehensive driver of drought severity considering different drought types (S M Vicente-Serrano et al., 2020). Here, we have demonstrated that AED mostly affects SPEI during periods of low precipitation. From a hydrological perspective, AED during low precipitaion periods would contribute to dry the soil until soil moisture is depleted (A Park Williams et al., 2020), given that AED would be the upper limit of ET. AED would increase free water evaporation and water consumption by irrigated lands; all of these aspects would increase hydrological drought severity. From agricultural and ecological perspectives, AED is a better proxy of vegetation stress than ET, making it an important input of any drought metric including SPEI. This is simply because under dry conditions, characterized by low soil moisture levels, ET will be limited by leaf stomata regulation (Chaves et al., 2016). As such, ET would be less sensitive to AED increases, which would enhance plant stress, with a subsequent reduction in leaf photosynthesis, carbohydrate assimilation, secondary growth and ultimately xylem embolism and plant mortality in the most critical cases. Therefore, the sensitivity of SPEI to AED during anomalous low precipitation periods can give strong indications on the reinforced role of AED in determining the severity of environmental and hydrological drought conditions.

Other studies have suggested that soil moisture simulations by coupled land-atmosphere models would be better metrics of dryness than climate drought indices including SPEI (e.g. Greve et al. 2019; Berg and Sheffield 2018). Irrespective of the wide spectrum of uncertainty introduced in this kind of models when reproducing the temporal variability of soil moisture observations (see Stillman et al. 2016; Ford and Quiring 2019; Yuan and Quiring 2017), we stress that the enhanced role of AED on plant dryness under low precipitation periods would not be well-recorded if we only consider soil moisture but we do not assess the AED influence. Moreover, several studies agree that the projections of soil moisture and SPEI for future scenarios are almost identical (see Vicente-Serrano et al. 2019; Xu et al. 2019; Feng et al. 2017), and even comparable to those suggested by PDSI (Dai et al., 2018).

Importantly, we would like to highlight some issues related to the possible goodness of SPEI for drought assessment in future scenarios. First, the adequate sensitivity of SPEI to AED identified in this study would be independent of any possible uncertainties in AED evolution in the upcoming decades. Second, SPEI is capable of including the possible influence of CO_2 atmospheric concentrations, which could affect AED in the future (Milly & Dunne, 2016; Roderick et al., 2015) since it is not constrained by any AED metric. Specifically, although there exist uncertainties related to the possible role of CO_2 concentrations on AED (B. Cook et al., 2018; S M Vicente-Serrano et al., 2020), the theoretical capacity of SPEI to adequately record the impacts of AED during low precipitation periods would be independent of this issue. Regardless of AED behavior in response to the impact of CO_2 concentrations, this would not affect the overall accuracy of SPEI in capturing the specific role of AED during low precipitation periods. Indeed, any future scenarios of a decrease in precipitation over some periods of regions would correspond to an increase in the sensitivity of SPEI to AED. However, this would be closely related to the expected role of this variable in the context of reinforcing hydrological and environmental drought conditions.

4. Conclusions

This study provides a global characterization of the sensitivity of the Standardized Precipitation Evapotranspiration Index (SPEI) to the atmospheric evaporative demand (AED). Results demonstrate that:

- Drought severity (as suggested by SPEI values) is mostly driven by precipitation variability in the majority of the land regions, with the exception of the most arid regions worldwide.
- In arid regions, AED contributes significantly to drought evolution. Importantly, this study stresses that the sensitivity of SPEI to AED is modulated largely by precipitation amounts, with a more pronounced role of AED in drought behavior during periods of low precipitation.
- SPEI did not overestimate the role of AED during normal and humid periods, in which the influence of AED on the severity of hydrological, agricultural and environmental drought severity should be negligible.
- Moreover, this influence is not spatially homogeneous worldwide, as humid regions showed less sensitivity of SPEI to AED, even during the driest periods.

Overall, these spatial and temporal patterns make SPEI a highly suitable and recommended drought metric to monitor and quantify current and future drought severity under different global climatic conditions.

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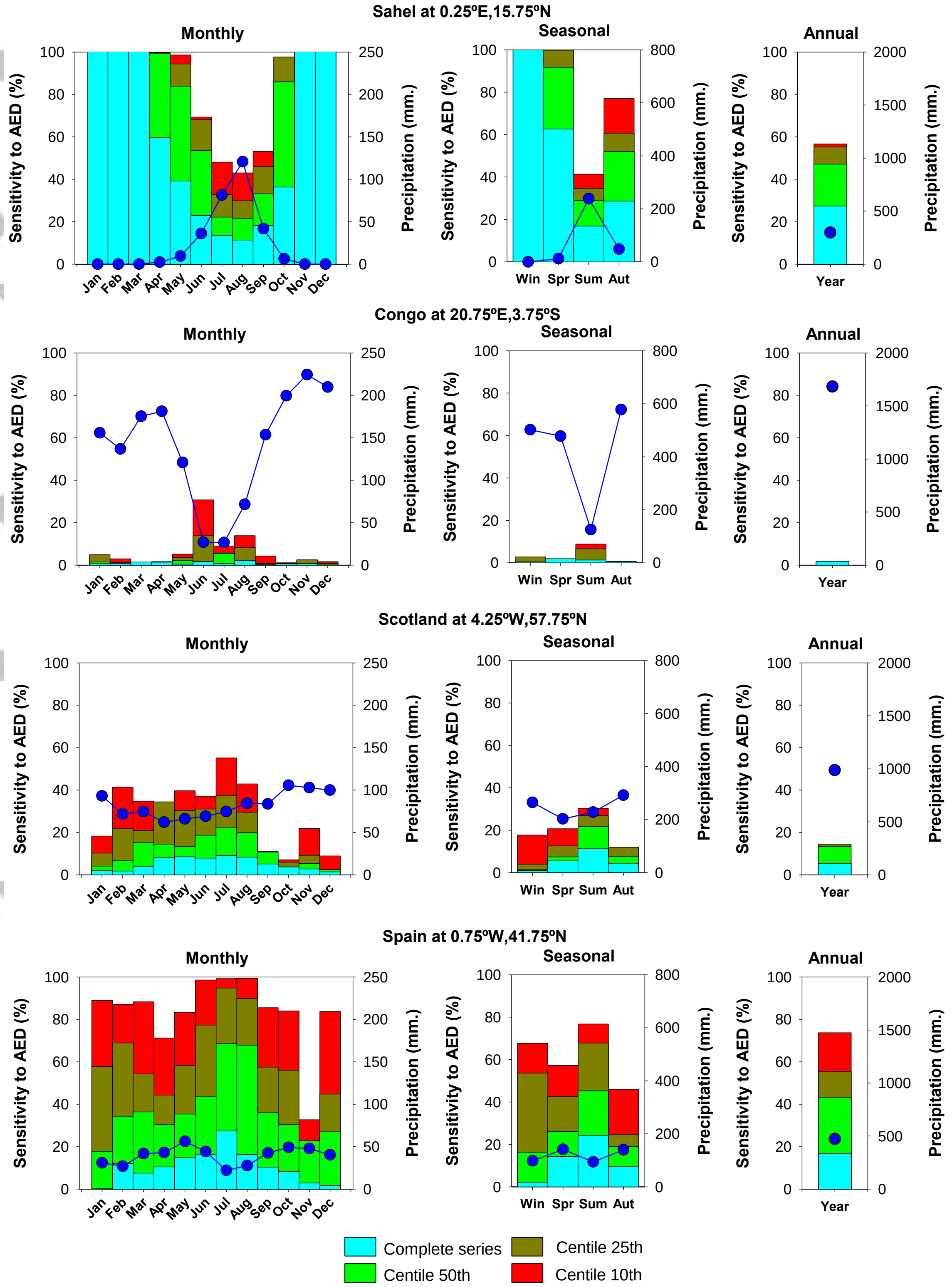


Figure 1: Sensitivity of SPEI to AED calculated for four different regions worldwide, considering different precipitation thresholds (complete precipitation series and centiles 50th, 25th and 10th). Blue circles represent the average precipitation.

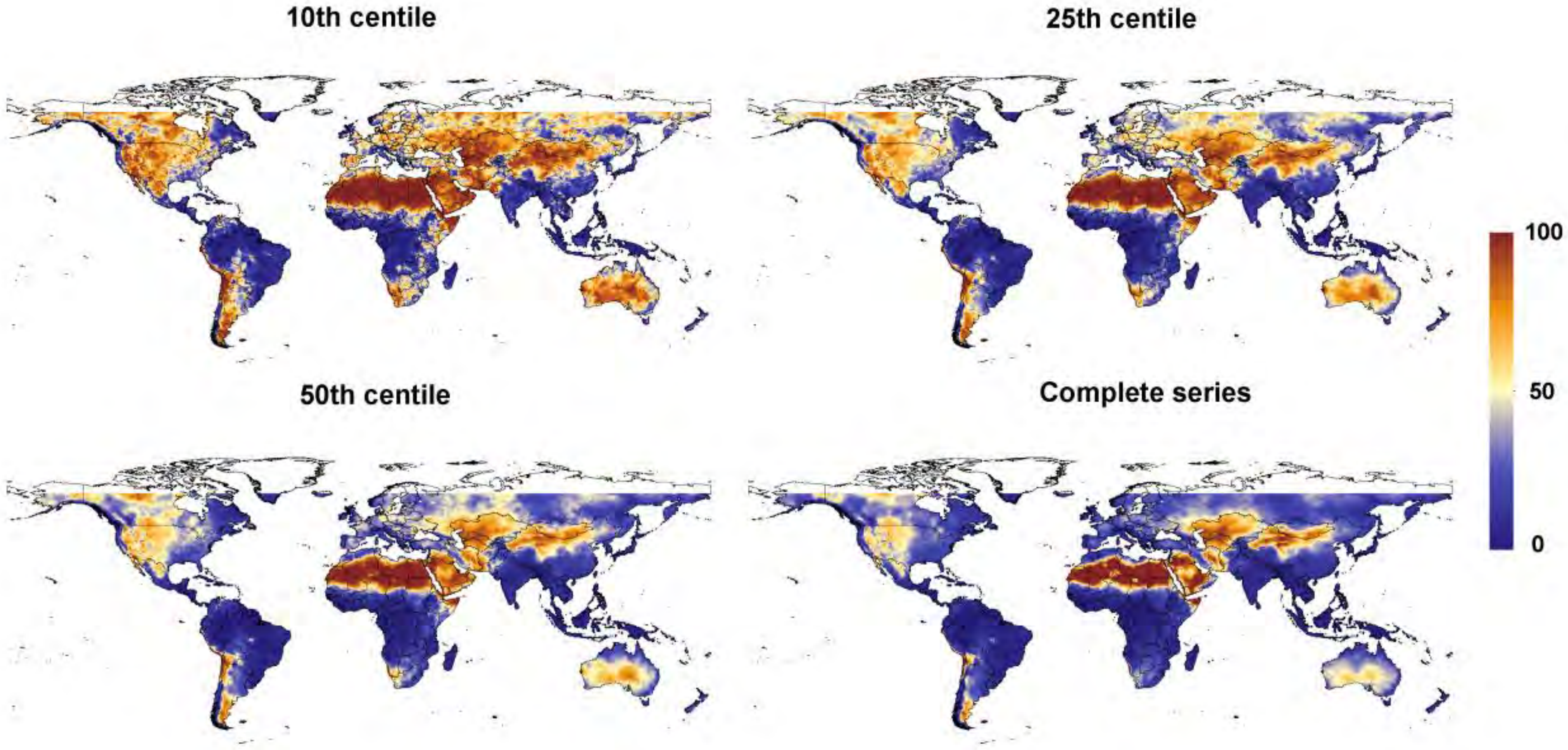


Figure 2: Spatial distribution of the sensitivity of SPEI to AED at the annual scale (SPEI at 12-month for December). The sensitivity was calculated for the complete series and the series of P-AED for different precipitation amounts (i.e. 10th, 25th and 50th).

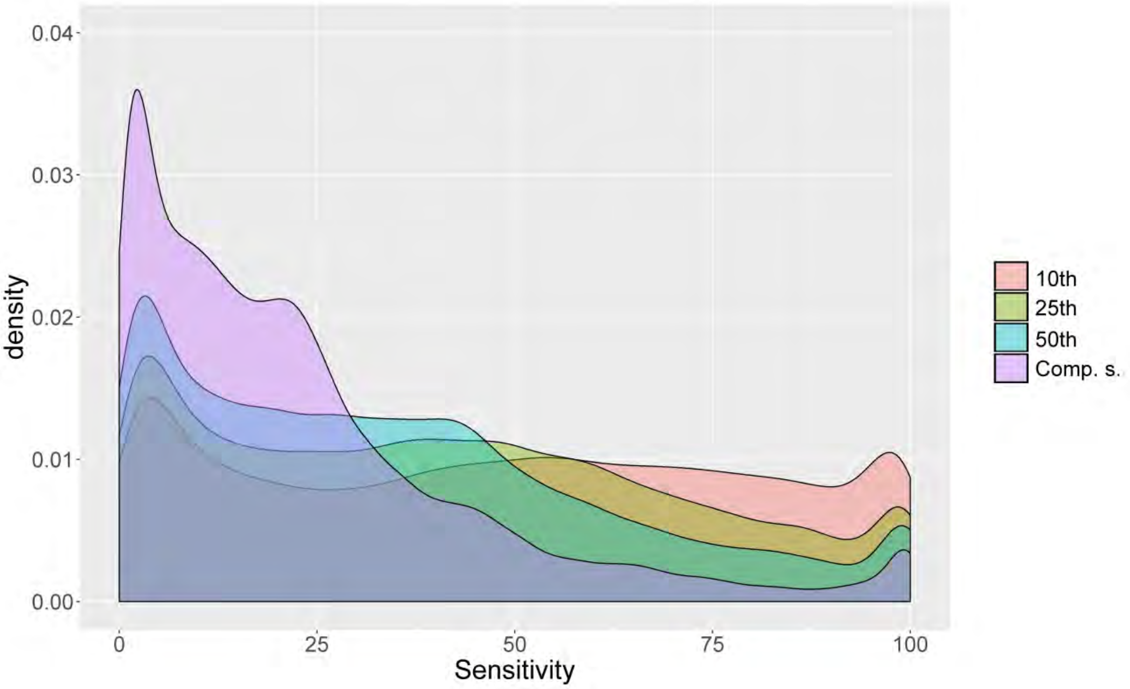


Figure 3: Density plot showing the sensitivity of SPEI to AED worldwide at the annual scale, considering the complete series and precipitation series corresponding to the 10th, 25th and 50th centiles of annual precipitation.

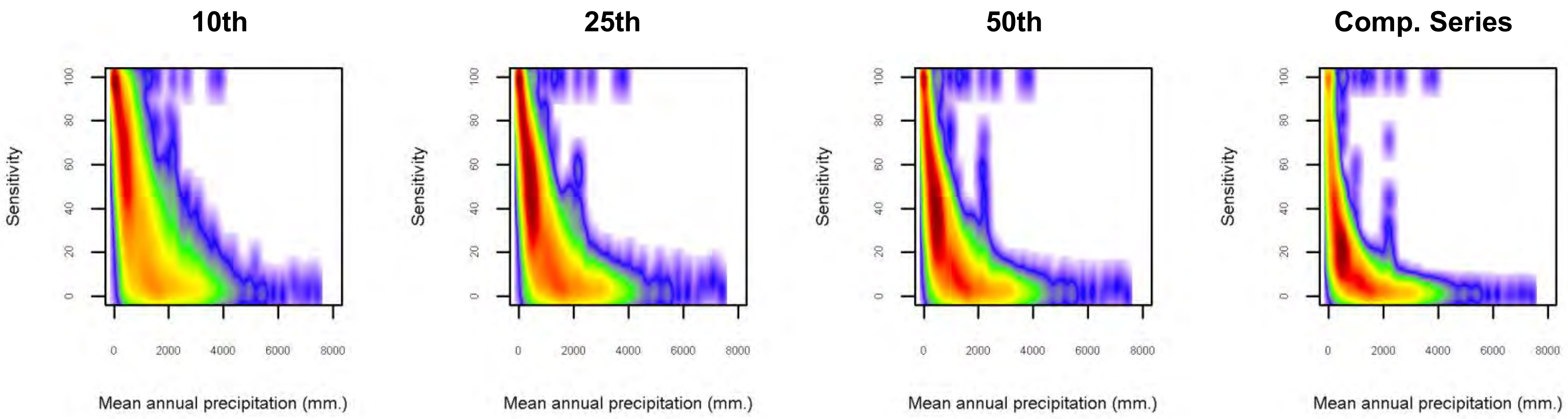
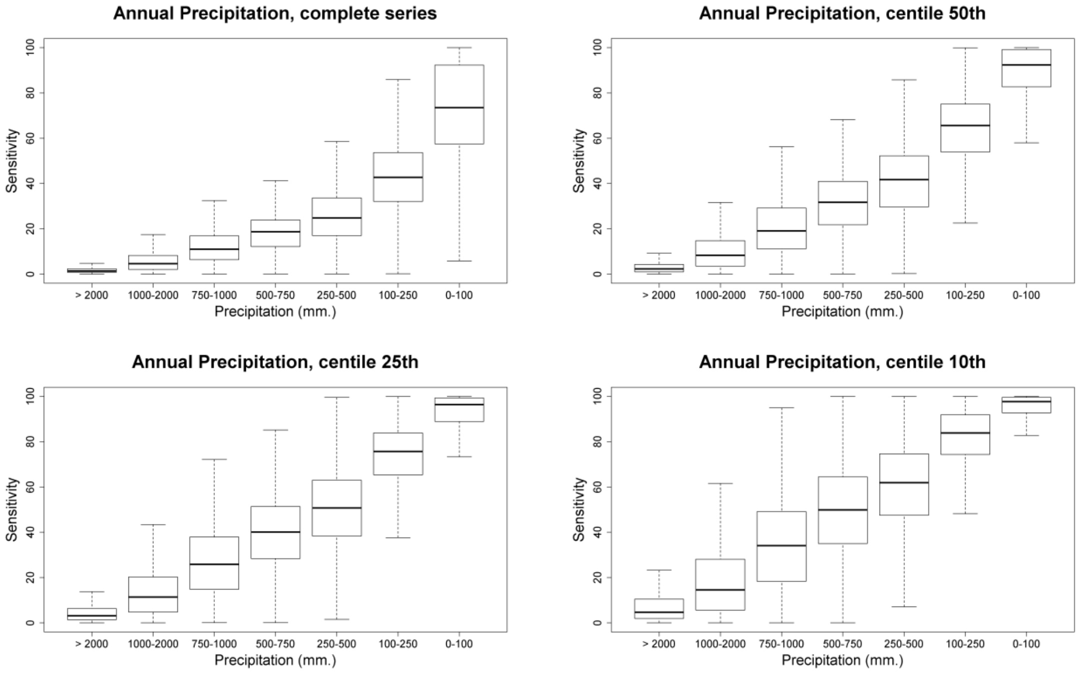


Figure 4: Relationship between the mean annual precipitation and the sensitivity of SPEI to AED considering the annual series. The plots consider the complete series and the precipitation series during the years corresponding to the 10th, 25th and 50th of annual precipitation. Colors represent the point density (red: high density, blue: low density).



Annual Precipitation, complete series

Annual Precipitation, centile 50th

Annual Precipitation, centile 25th

Annual Precipitation, centile 10th

Figure 5: Boxplots showing the sensitivity of SPEI to AED at the annual scale for the complete series (centile 100th) and the precipitation series corresponding to the 10th, 25th and 50th of annual precipitation. The central solid line indicates the median. The whiskers represent the 10th and the 90th, while the 25th and the 75th are plotted as the vertical lines of the bounding boxes.