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Contribution of precipitation and reference evapotranspiration to drought indices under different climates

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SUMMARY

In this study we analyzed the sensitivity of four drought indices to precipitation (P) and reference evapotranspiration (ETo) inputs. The four drought indices are the Palmer Drought Severity Index (PDSI), the Reconnaissance Drought Index (RDI), the Standardized Precipitation Evapotranspiration Index (SPEI) and the Standardized Palmer Drought Index (SPDI). The analysis uses long-term simulated series with varying averages and variances, as well as global observational data to assess the sensitivity to real climatic conditions in different regions of the World. The results show differences in the sensitivity to ETo and P among the four drought indices. The PDSI shows the lowest sensitivity to variation in their climate inputs, probably as a consequence of the standardization procedure of soil water budget anomalies. The RDI is only sensitive to the variance but not to the average of P and ETo. The SPEI shows the largest sensitivity to ETo variation, with clear geographic patterns mainly controlled by aridity. The low sensitivity of the PDSI to ETo makes the PDSI perhaps less apt as the suitable drought index in applications in which the changes in ETo are most relevant. On the contrary, the SPEI shows equal sensitivity to P and ETo. It works as a perfect supply and demand system modulated by the average and standard deviation of each series and combines the sensitivity of the series to changes in magnitude and variance. Our results are a robust assessment of the sensitivity of drought indices to P and ETo variation, and provide advice on the use of drought indices to detect climate change impacts on drought severity under a wide variety of climatic conditions.

1. Introduction

Determining the effect of climate change on drought severity is difficult due to the lack of long-term series and accurate measurements of streamflows, soil moisture, lake levels, etc. This situation is made worse by the effects of water management and land transformation on these series, making a separation of a climatic and antrophogenic signal difficult. For this reason, the assessments of climate warming impacts on drought trends at the global scale have been based on climatic drought indices (e.g., Sheffield et al., 2012; Dai, 2013; Van der Schrier et al., 2013; Beguería et al., 2014), which can be computed for the entire world given the availability of global climate data. These indices are calculated from time series of precipitation (P) and reference evapotranspiration (ETo), and in general they are good proxies to determine drought conditions in a variety of environmental, hydrological and agricultural systems (Vicente-Serrano et al., 2012).

The results of global studies analyzing the effect of warming processes on drought severity differ in the magnitude of the drought trends and in their spatial patterns as a consequence of differences in the forcing precipitation data sets used (Trenberth et al., 2014), the models used to estimate ETo and the meteorological data sets used to calculate ETo. Sheffield et al. (2012) analyzed, at the global scale, the influence of using a simple empirical temperature-based formulation and a more physical model, based on several meteorological variables, to estimate ETo. They showed that, globally averaged, differences in the variability and change of drought indices may relate to the parameterization used to estimate ETo. Nevertheless, strong differences in the magnitude of ETo changes may be obtained using different methods to estimate ETo (e.g., Donohue et al., 2010; Vicente-Serrano et al., 2014a, van der Schrier et al., 2013).

These observations pose the question to the sensitivity of the different indices to variations in P and ETo; a matter which has

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seen only limited attention in the scientific literature A few studies based on the Palmer Drought Severity Index (PDSI) showed contradictory or opposite results. Guttman (1991) analyzed the sensitivity of the Palmer Drought Hydrological Index (similar but slightly simpler than the PDSI) to P and ETo in USA, and found that the effect of temperature anomalies (used to obtain ETo) are insignificant compared to the effect of precipitation anomalies. On the contrary, Hu and Willson (2000) analyzed the sensitivity of the PDSI in central United States and showed that the PDSI can be equally affected by temperature and precipitation, when both have similar magnitudes of anomalies.

The Standardized Precipitation Index (SPI) (McKee et al., 1993) is put forward by the World Meteorological Organization (WMO) as universal drought index (Hayes et al., 2011; WMO, 2012). Strong points favoring the use of the SPI are its capacity to be calculated on different time-scales to adapt to the varied response times of typical hydrological variables to precipitation deficits. It allows detecting different drought types that affect different systems and regions. Although the SPI has shown to be useful for drought monitoring and early warning (e.g., Hayes et al., 1999), deficiencies have also been noticed related to its inability to detect drought conditions determined not by a lack of precipitation but by a higher than normal atmospheric evaporative demand. This situation may be very relevant under extreme heat waves (Beguería et al., 2014). For climate change studies, the inability of the SPI to capture an increased evaporative demand related to global warming is problematic as well (Dai, 2013; Beguería et al., 2014; Cook et al., 2014). For this reason, studies on recent drought trends (Sheffield et al., 2012; Vicente-Serrano et al., 2014b) and drought scenarios under future climate change projections (e.g., Hoerling et al., 2012; Cook et al., 2014) are based on drought indices that consider not only precipitation but also the atmospheric evaporative demand. Using these indices, Cook et al. (2014) showed that increased ETo not only intensifies drying in areas where precipitation is already reduced, it also drives areas into drought that would otherwise experience little drying or even wetting from precipitation trends alone.

In this study we analyze the relative contribution of variations in P and ETo to the spatial and temporal variability of four drought indices that make use of both variables in their calculation: (i) the self calibrated Palmer Drought Severity Index (PDSI) (Wells et al., 2004); (ii) the Reconnaissance Drought Index (RDI) (Tsakiris et al., 2007); (iii) the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010a); and (iv) the Standardized Palmer Drought Index (SPDI) (Ma et al., 2014). The analysis includes a theoretical assessment using long-term simulated series under different average and variance constraints for both P and ETo, and a global study based on gridded datasets and instrumental series from meteorological stations. The motivation to include these four indices is that they all are based on a combination of P and ETo which we think is more realistic than using only P. Temporal agreement between hydrological and climatic drought indices using ETo in their formulations is strong even considering different climate conditions (López-Moreno et al., 2013; Lorenzo-Lacruz et al., 2013; Haslinger et al., 2014; Törnros and Menzel, 2014). In addition, the relationship of these indices with vegetation growth and activity, both highly determined by soil water availability, is quite strong (Orwig and Abrams, 1997; Vicente-Serrano et al., 2013; Ivits et al., 2014).

2. Methods

2.1. Drought indices

2.1.1. The Palmer Drought Severity Index

The PDSI (Palmer, 1965; Karl, 1983, 1986; Alley, 1984) enables measuring both wetness (positive values) and dryness (negative values), based on the supply and demand concepts of the water balance equation, and thus incorporates prior precipitation, moisture supply, runoff, and evaporation demand at the surface level. Palmer (1965) used data from a few locations in the American mid-west to standardize the index, which restricts its application around the world (see Akinremi et al., 1996; Guttman et al., 1992; Heim, 2002). This problem was solved by the self-calibrated PDSI (Wells et al., 2004), which calibrates the PDSI using data specifically suitable for each location, which makes it more spatially comparable. In this study we use the self-calibrated version of the PDSI. There is a number of studies that have revised the advantages and limitations of the PDSI for drought analysis and monitoring. On the positive side, it allows to measure both wetness (positive values) and dryness (negative values), based on the supply and demand concepts of the water balance equation, and thus incorporates prior precipitation, moisture supply, runoff and evaporation demand at the surface level (Karl, 1983, 1986; Alley, 1984). In addition to the above mentioned problems of spatial comparability, other different issues and deficiencies in the use of the PDSI for drought quantification and monitoring have been widely reviewed. They are related to its sensitivity to the soil water field capacity (Karl, 1986; Weber and Nkemdirim, 1998) and its lack of adaptation to the intrinsic multi-scalar nature of drought (Vicente-Serrano et al., 2011). Mishra and Singh (2010) provided a revision of the advantages and limitations of different drought indices, and they also stressed the limitations of the PDSI related to runoff underestimation and slow response to developing and diminishing droughts.

2.1.2. The Reconnaissance Drought Index

The RDI (Tsakiris and Vangelis, 2005) is calculated with P and ETo and is based on the approach similar to calculate the aridity index (AI); i.e., as the quotient between P and ETo (UNESCO, 1979), which can be computed at different time-scales. This quotient is standardized according to the mean and standard deviation of the series, assuming that P/ETo follows a log-normal distribution. Interpretation of the RDI is similar to that of the SPI. The RDI has been used to assess drought variability and trends in some regions (e.g., Khalili et al., 2011; Zarch et al., 2011; Banimahd and Khalili, 2013; Vangelis et al., 2013). There are not studies that have analyzed the advantages and shortcomings of the RDI, but among the main theoretical limitations of this drought index it is highlighted that gives no valid values when ETo is equal to 0, which is very common in cold regions in winter, mainly when ETo is calculated using empirically temperature-based methods.

2.1.3. The Standardized Precipitation Evapotranspiration Index

Vicente-Serrano et al. (2010a, 2010b, 2011, 2012) and Beguería et al. (2014) provided complete descriptions of the theory behind the SPEI, the computational details, and comparisons with other popular drought indicators such as the PDSI and the SPI. The SPEI is based on a monthly climatic water balance (P-ETo), which is adjusted using a 3-parameter log–logistic distribution. The values are accumulated at different time scales and converted to standard deviations with respect to average values. Some authors have criticized the SPEI in relation to the PDSI arguing that the SPEI does not represent soil water content (Dai, 2011; Joetzjer et al., 2013) but the aim of the SPEI is to represent departures in climatological drought, the balance between the water availability and the atmospheric water demand, and is therefore slightly different from the drought índices that include a simplified soil moisture budget which relate their index to the latter quantity (see further discussion in Beguería et al., 2014).