Journal of Hydrology 554 (2017) 292–305

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Combined use of relative drought indices to analyze climate change impact on meteorological and hydrological droughts in a Mediterranean basin

P. Marcos-Garcia *, A. Lopez-Nicolas, M. Pulido-Velazquez

Research Institute of Water and Environmental Engineering (IIAMA), Universitat Politècnica de València, Camí de Vera s/n, 46022 Valencia, Spain

ARTICLE INFO

Article history:
Received 4 May 2017
Accepted 14 September 2017
Available online 18 September 2017
This manuscript was handled by A. Bardossy, Editor-in-Chief, with the assistance of Alin Andrei Carsteanu, Associate Editor

Keywords:
Standardized drought indices
Climate change impact
Meteorological droughts
Hydrological droughts
Evapotranspiration

ABSTRACT

Standardized drought indices have been traditionally used to identify and assess droughts because of their simplicity and flexibility to compare the departure from normal conditions across regions at different timescales. Nevertheless, the statistical foundation of these indices assumes stationarity for certain aspects of the climatic variables, which could no longer be valid under climate change. This contribution provides a framework to analyze the impact of climate change on meteorological and hydrological droughts, considering shifts in precipitation and temperature, adapted to a Mediterranean basin. For this purpose, droughts are characterized through a combination of relative standardized indices: Standardized Precipitation Index (rSPI), Standardized Precipitation Evapotranspiration Index (rSPEI) and a Standardized Flow Index (rSFI). The uncertainty and the stationarity of the distribution parameters used to compute the drought indices are assessed by bootstrapping resampling techniques and overlapping coefficients. For the application of the approach to a semiarid Mediterranean basin (Jucar River Basin), the Thornthwaite scheme was modified to improve the representation of the intra-annual variation of the potential evapotranspiration and low flow simulation in hydrological modelling was improved for a better characterization of hydrological droughts. Results for the Jucar basin show a general increase in the intensity and magnitude of both meteorological and hydrological droughts under climate change scenarios, due to the combined effects of rainfall reduction and evapotranspiration increase. Although the indicators show similar values for the historical period, under climate change scenarios the rSPI could underestimate the severity of meteorological droughts by ignoring the role of temperature.

1. Introduction

Unlike aridity, a permanent feature of climate in low rainfall areas, droughts are temporary deviations that can happen in any climatic region (Wilhite 2000; Tallaksen and Van Lanen, 2004). Droughts, generally defined as divergences from normal conditions on water availability, often start with a prolonged lack of precipitation and then propagate to other components of the hydrological cycle. Persistent droughts can lead to a significant depletion of reservoirs' storages and groundwater levels, with a subsequent broad range of socio-economic and environmental impacts. According to the latest report of the Intergovernmental Panel on Climate Change (IPCC, 2014a), the current emission of greenhouse gases will increase global warming and produce durable changes in the climate system, raising the likelihood of extreme events. Under those conditions, droughts could become more frequent and severe around the world (Dai, 2013), with a growing impact on water resources. In this context, the Mediterranean region emerges as a prominent regional climate change hotspot (Diffenbaugh and Giorgi, 2012). The most relevant key climatic drivers for water availability are precipitation, temperature, evaporative demand (which depends on net radiation), atmospheric humidity, wind speed and temperature (Bates et al., 2008). The current climate models are able to reproduce the observed continental-scale surface temperature patterns and trends with assurance, but the level of performance for large scale patterns of precipitation is lower than that of temperature (IPCC, 2014b). This fact poses high uncertainty regarding future climate projections and therefore, on the effects of climate change on drought severity at the regional level (Burke and Brown, 2007). Particularly in areas with high precipitation variability, such as the Mediterranean region, the drought patterns derived from the outputs of global climatic models are not consistent (Vicente-Serrano et al., 2004).

In recent years, many studies have been conducted to assess the potential impact of climate change on meteorological, agricultural

* Corresponding author.
E-mail addresses: patmarg5@upv.es (P. Marcos-Garcia), anloni@upv.es (A. Lopez-Nicolas), mapuve@hma.upv.es (M. Pulido-Velazquez).

http://dx.doi.org/10.1016/j.jhydrol.2017.09.028
0022-1694/

and hydrological droughts in different regions of the world, using different indicators depending on drought types (e.g. reviews by Mishra and Singh, 2010; Zargar et al., 2011; Pedro-Monzonís et al., 2015). Most of these studies are conducted using well-established indices, such as the Palmer Drought Severity Index (PDSI; Palmer 1965), based on soil water balance equation, or the Standardized Precipitation Index (SPI; McKee et al., 1993), based on a probabilistic approach for precipitation to evaluate meteorological droughts. Although the benefits and drawbacks of these indices for the analysis of historical droughts have been widely discussed (Alley, 1984; Dai, 2011; Hayes et al., 1999), few authors have addressed the specific limitations of the traditional indicators under a nonstationary, climate change context. Vicente-Serrano et al. (2010) pointed out the inability of SPI to identify the role of global warming in future drought conditions, since it neglects the effect that a temperature increase and subsequent evapotranspiration increase can have on droughts. To overcome this issue, they propose a new climatic drought index (the Standardized Precipitation Evapotranspiration Index (SPEI)), which combines the sensitivity of PDSI to changes in evaporation demand (caused by temperature fluctuations and trends) with the simplicity of calculation and the multi-temporal nature of the SPI. Nevertheless, it is important to note that potential evapotranspiration (PET) formulations introduce additional uncertainty to that due to the climate models (Kay and Davies, 2008). The use of standardized drought indices is appealing for many reasons: the procedure is simple and can be generalized for assessing different types of droughts (e.g. Shukla and Woods, 2008), they are comparable in time and space (Hayes et al., 1999). Nevertheless, the traditional statistical foundation of these indices cannot be used in climate change impact assessments, as they would provide approximately the same distributions for both present and changed climates regardless of the changes in the climate conditions (Dubrovsky et al., 2009; Zargar et al., 2014).

In this paper we study the impacts of climate change on meteorological and hydrological droughts in a Mediterranean basin through a combination of relative standardized indices that allow for the consideration of predicted shifts in precipitation and temperature. For dealing with the uncertainty on the parameters of the distributions used to compute the drought indices, bootstrapping techniques are applied to compute the overlapping coefficient (OVL) for each parameter between the historical and future density functions. The catchment and climate characteristics of the case require modifications to the method for PET estimation and to the conceptual hydrological simulation model (improved simulation of low-flow conditions to better represent hydrological droughts). The catchment characteristics help to explain the spatial differences on the historical and future drought characteristics.

In the upcoming sections, the overall approach and its adaptation to the sui-generis characteristics of a Mediterranean basin are presented. Then, drought characterization under climate change conditions using standardized relative indices is explained. The study area, the climate change projections, and the bias correction method are described. The specific modifications for adapting the method to the case study, including the hydrological simulation and the PET estimation methodology are presented. Finally, the paper shows the main results, the discussion and the main conclusions are presented.

2. Method

2.1. Overall approach

The selected methodology (Fig. 1) involves three main steps: future time series generation, hydrological modeling and drought assessment.

A) Time series generation under climate change:

This step first requires selecting a set of climate change projections, using the outputs from a combination of Global Circulation Models (GCMs) and Regional Circulation Models (RCMs). These future projections are based on the new IPCC scenarios, the Representative Concentration Pathways (RCPs), which define four different pathways of greenhouse emissions and atmospheric concentrations, air pollutant emissions and land use (IPCC, 2014b). The main advantage of the new RCP scenarios over the Special Report Emissions (SRES) scenarios is that the impacts of the international agreements and efforts to mitigate the gas emissions are considered.

GCMs reproduce physical processes and the effect of an increase of greenhouse gases concentration in the climate system. Nevertheless, GCMs present the disadvantage of scale or resolution, normally having a horizontal resolution of between 250 and 600 km, 10–20 vertical layers in the atmosphere (IPCC, 2014a). For this reason, the Regional Climate Models (RCMs) are used to perform the climate change projections with more accuracy at the local level, through downscaling techniques. The selection is made based on the goodness-of-fit between the observed and the simulated values for the control period.

Although RCMs downscale the outputs of GCMs, precipitation and temperature simulations from RCMs are known to be biased and need to be post-processed in order to produce reliable estimates of expected local climate conditions (Fowler et al., 2007). Several bias correction methods have been developed, mostly based on statistical transformations to adjust selected aspects of the distribution of RCMs so that the new distribution resemble the original (e.g., Teutschbein and Seibert, 2012; Gudmundsson et al., 2012). In this research we apply the equidistant "quantile mapping" method (Li et al., 2010) to correct the bias of future climatic projections by adjusting the cumulative distribution function (CDF) for the future period based on the difference between the model and the observed CDFs for the control (baseline) period. The method has been proved to be more efficient in reducing biases than the traditional CDF mapping method for changing climates, especially for the tails of the distribution (Li et al., 2010). For the implementation of the bias correction process, we used the statistical package "qmap" for post-processing the climate model output (Gudmundsson et al., 2012). The tool, implemented in R statistical software (R development team, 2015), allows to use different fitting options and to select the transformation for modelling the quantile-quantile relation between the observed and the modelled time series, choosing quantiles that are regularly spaced through least-square regression.

B) Hydrological modeling:

To assess the climate change impacts on hydrological droughts, it is necessary to simulate future flows (river discharges), using the bias corrected temperature and precipitation variables as inputs to a hydrological model. The most simple and straightforward method to estimate the potential evapotranspiration (PET) is the Thornthwaite model. However, as discussed in Section 4.3, this approach has some drawbacks when applied to semiarid areas, where it may underestimate the PET. In our case, we apply a conceptual, lumped-parameter Temez model, modified to improve the representation of low flows, which is essential in the characterization of hydrological droughts. The application of this methodology to the case study is further developed in Sections 4.2 and 4.3.

C) Drought assessment:

Drought analysis is based on the use of relative standardized indices (rSPI, rSPEI and rSFI) and the "run theory" (Yevjevich,