Atmospheric Research 194 (2017) 268–280

Contents lists available at ScienceDirect

Atmospheric Research

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

Influence of mathematical and physical background of drought indices on their complementarity and drought recognition ability

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ARTICLE INFO

Keywords:
Drought modelling
Indicators
Time series similarity
Drought recognition ability

ABSTRACT

The aim of this study is to test how effective and physically correct are the mathematical approaches of operational indices used by relevant National Agencies across the globe. To do so, the following indices were analysed Standardized Precipitation Index (SPI) -1, 3, 6, 12 and 24, Standardized Precipitation – Evapotranspiration Index (SPEI) – 1, 3, 6, 12 and 24, Effective Drought Index (EDI) and Index of Drying Efficiency of Air (IDEA). To make regions more comparable to each other and follow the spatial development of drought SPI index was advised by World Meteorological Organisation to be used widely by official meteorological services. The SPI and SPEI are used for Drought Early Warning in the USA, National Drought Mitigation Center and NASA, and in the EU by the European Drought Centre (EDC) and in the Balkan Region by National Meteorological Agencies. The EDI Index has wide application in Asia. In this paper four different issues were investigated: 1) how the mathematical method used in a drought indicator's computation influence drought indices' (DI) comparative analyses; 2) the sensitivity of the DIs on any change of the length of observational period; 3) similarities between the DIs time series; 4) and how accurate DIs are when compared to historical drought records. Results suggest that it is necessary to apply a few crucial changes in the Drought Monitoring and Early Warning Systems: 1) reconsider use of SPI and SPEI family indices as a measure of quality of other indices; and for Drought Early Recognition Programs 2) switch to DIs with a solid physical background, such as EDI; 3) Adopt solid physics for modelling drought processes and define the physical measure of drought, e.g. EDI and IDEA indices; 4) investigate further the IDEA index, which, supported by our study as well, is valuable for simulation of a drought process.

1. Introduction

A drought impact is an observable loss or change at a specific time due to drought occurrence. Drought risk management involves hazards, exposure, vulnerability and impact assessment, a drought early warning system (DEWS) (monitoring and forecasting), and preparedness and mitigation (WMO, UNCCD and FAO, 2013). Hence, it is important that drought indicators or indices both accurately reflect and represent the impacts that are being experienced during droughts. As droughts evolve, the impacts can vary by region and by season. Drought early warning systems typically aim to track, assess and deliver relevant information concerning climatic, hydrologic and water supply conditions and trends. Ideally, they have both a monitoring (including impacts) component and a forecasting component. The objective is to provide timely information in advance of, or during, the early onset of drought to prompt action (via threshold triggers) within a drought risk management plan as a means of reducing potential impacts. A diligent, integrated, approach is vital for monitoring such a slow-onset hazard (WMO, 2016).

Drought indices should be solid proof that drought will occur. As a tool DIs have to be meticulous and their measure has to be clear and understandable. It should be strictly define what DI-s measure. Values of DI-s have to reflect drought effects and obey the physical laws. As a measure for drought, DI-s should be mathematically specified so that

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http://dx.doi.org/10.1016/j.atmosres.2017.05.006
Received 29 August 2016; Received in revised form 21 March 2017; Accepted 5 May 2017

describe the physics of drought formation and its cause. Hence, the aim of this research is to determine how similar drought indices actually are. Namely, since the mathematical specification of drought indices influence the representation of the physical process of a drought and drought recognition ability, it is of crucial importance to reveal what are we actually comparing and how compatible are these indices for comparison. The study also questions the accuracy of directly compared outputs of various drought indices and suggests which drought index is the best and most suitable for an observed region.

2. Theory

As noted by Wilhite et al. (2007) due to the number of 'affected groups and sectors associated with drought, the geographic size of the area affected, and the difficulties in quantifying environmental damages and personal hardships, the precise determination of the financial costs of drought is a formidable challenge. Those are some of the reasons for which is often said that drought is the most complex of all natural hazards, and more people are affected by it than any other hazard (FEMA, 1996; Svoboda et al., 2002; Wilhite and Buchanan-Smith, 2005; Wilhite et al., 2005; Dutra et al., 2014; Maliva and Missimer, 2012; Tallaksen et al., 1997; Heim, 2002; Tallaksen and van Lanen, 2004; Heim and Brewer, 2012; Xu et al., 2014; Song et al., 2015).

Due to its' complexity, challenges to measure drought led to the development of various drought indicators and indices (DIs) over the last couple of decades. The availability of data and methods has influenced the course of DI evolution. Most of the available drought indices have been developed for the specific regions and have limited use under the different climatic conditions (Jain et al., 2015; Mohammad et al., 2014).

Great variety of the measurement methodologies has raised academic concern about the complementarities of previously published results and more importantly about the actual meaning of these drought indicators. In this respect, several attempts have been made so far to analyse the appropriateness in describing the drought characteristics for a particular region by testing different indices (Keyantash and Dracup, 2002; Ntale and Gan, 2003; Morid et al., 2006; Barua et al., 2011; Dogan et al., 2012; Jain et al., 2015; Eshghabad et al., 2014; Hao and Agha Kouchak, 2013; Smakhtin and Hughes, 2004; Agwata, 2014; Bayarjargal et al., 2006; Nauman et al., 2014; Gosling et al., 2012; Zargar et al., 2011; Brown and Matlock, 2011; Byun and Kim, 2010; Mishra and Singh, 2010; Niemeyer, 2008; Guttman, 1998; Rao and Voeller, 1997, Xu et al., 2014, Huang et al., 2015). Smakhtin and Hughes (2007) developed Spatial and Time Series Information modelling (SPATSIM) software for automated estimation of drought severity combining five different drought indices. Pandey et al. (2008) used SPATSIM for a drought study of Orissa, India and found that EDI performed better than other DIs. Similarly, Dogan et al. (2012) compared six meteorological drought indices and indicated that each drought index identified the drought characteristics differently. They computed and observed the variation in severity values and duration of a drought event using different indices and concluded that EDI performed better than other tested indicators for monthly rainfall changes in semi-arid Kenya closed basin and Turkey (Jain et al., 2015).

Nevertheless, WMO (2016) gives overview of drought indices/indicators. Most noticeable is that WMO (2016) along with other official agencies (Gudmudson et al., 2014) promote utilization of SPI family of indices, even though these do not provide important information about the actual water availability. More concerning is that majority of National agencies are adopting the SPI family in their Drought Early Warning systems in spite of obvious weakness of SPI. Such trends raise the question if the leading practitioners in the field are using the best possible tool for drought recognition. Recent lack of mitigation of droughts in North America (California 2012–2016) confirmed doubts about the effectiveness of SPIs as a tool for drought early warning.

3. Research methodology

3.1. Methodology of DIs mathematical method consistency and liability assessment

Beside the Effective Drought Index (EDI) based on monthly precipitation data (Byun and Wilhite, 1999) and the Index of Drying Efficiency of Air (IDEA) (Frank, 2016), we analysed the variations of the Standardized Precipitation Index (SPI) (McKee et al., 1993) (1, 3, 6, 12 and 24) and the variations of Standardized Precipitation– Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) (1, 3, 6, 12 and 24). Research Procedure for assessing mathematical consistency and liability of DIs methodology:

(I) For each DI available calculation method was collected and executed. Only published and recognized codes for the computation of DIs were used, with an exception to IDEA, which as a result of drought modelling experiment based on air drying process (Frank, 2016), is still under development.

(II) Over 20 variations of DI's time series were generated. EDI_1 and EDI_2, IDEA_V1, and two models for SPI and/or were accepted in the study and have undergone the following testing: MODEL 1: SPI-3 (McKee et al., 1993), MODEL 2: SPI-1, SPI-3, SPI-6, SPI-12, SPI-24 (Vicente-Serrano et al., 2010; Stagee et al., 2015, 2016), SPEI (Vicente-Serrano et al., 2010) in nine variations on five time scales. For each adopted variation, an uninterrupted time series was generated for the research period 1951–2012.

(III) Time series of selected drought indicators were calculated for 7 meteorological stations across North Serbia (Table 1). Climatic characteristics were calculated on the base of the normal for period 1971–2000. Average sums of potential evapotranspiration (PET) are based on Penman-Montheith method (Allen et al., 1994). Stations with similar geographical and climatic characteristics were considered in the study to exclude potential source of biasness and random variation that could significantly distort study results.

(IV) Variability of DIs due to changes in methods of computational mathematics was tested:
   a. For SPI – two different models of computation were tested.

Table 1
Geographical and climatic characteristics of explored stations.

Station name	Abbr.	Elevation (m a.s.l.)	Latitude (N)	Longitude (E)	Mean P (mm year^{-1})	Mean PET (mm year^{-1})	Aridity index	Climate
Palic	PA	102	46° 06′	19° 46′	537.6	839.6	0.64	Subhumid
Novi Sad	NS	84	45° 20′	19° 51′	611.7	868.4	0.70	Subhumid
Sombor	SO	88	45° 46′	19° 09′	579.7	830.9	0.70	Subhumid
Zrenjanin	ZR	80	45° 24′	20° 21′	569.2	860.9	0.66	Subhumid
Kikinda	KI	81	45° 51′	20° 28′	538.1	882.9	0.61	Subhumid
Vrsac	VR	84	45° 09′	21° 19′	652.6	947.2	0.69	Subhumid
Sremska Mitrovica	SM	82	45° 06′	19° 33′	605.1	840.7	0.72	Subhumid