Improved Standard Precipitation Index and drought characteristics

Zekâi Şen

Engineering and Natural Sciences Faculty,
Istanbul Medipol University,
Beykoz, 34815, Istanbul, Turkey
Email: zsen@medipol.edu.tr
and
Center of Excellence for Climate Change Research,
Department of Meteorology,
King Abdulaziz University,
P.O. Box 80234, Jeddah 21589, Saudi Arabia
Email: zsen@kau.edu.sa

Abstract: In many regions of the world, and particularly in the eastern Mediterranean region, there is a general precipitation decrease tendency according to the global circulation model (GCM) and the regional climate change models (RegCM). Dry spells and their temporal occurrences as droughts affect water resources, and hence, agriculture and food securities may be endangered in such region. It is, therefore, necessary to foresee the future drought characteristics based on the historical records. Although the Standard Precipitation Index (SPI) provides dryness classifications, it cannot reflect the basic drought characteristics in the original hydro-meteorological records. The main purpose of this paper is to propose improved SPI (ISPI) approach for quantitative drought characteristics calculations. In order to support the insufficiencies in the classical SPI, a comparative study is presented with the ISPI method on the bases of drought duration, amount and intensity concepts. It is shown that especially the risk calculations have wide discrepancies, but the ISPI provides actual results. The application with objective results is presented for Istanbul European side, Turkey, meteorology station monthly precipitation records.

Keywords: drought; duration; global warming; intensity; precipitation; standard index.

Reference to this paper should be made as follows: Şen, Z. (2021) 'Improved Standard Precipitation Index and drought characteristics', *Int. J. Global Warming*, Vol. 23, No. 1, pp.1–10.

Biographical notes: Zekâi Şen graduated from Istanbul Technical University (ITU) in 1971 and the same year went to Imperial College and Technology, University of London and he received his DIC and MSc degrees in 1972. He worked for PhD on Stochastic Processes and Modelling Subjects and obtained the degree in 1974. He return back to Turkey and worked at ITU until 1980. In the same, year he is invited by the King Abdulaziz University, Faculty of Earth Sciences, Hydrogeology Department, where he worked until 1992. He continued his academic career at the ITU in the Aeronautics and Astronautics

Faculty, Meteorology Department. He obtained the retirement in 2014. He worked also at the King Abdulaziz University and Saudi Geological Survey. Currently, he is a staff member at the Istanbul Medipol University, Faculty of Engineering and Natural Sciences since 2017.

1 Introduction

Since time immemorial in the history, civilisations strived for water resources and fresh water edges such as lakes and rivers, which were the only settlement locations for human survival. The necessary precautions are taken based on daily experience against natural events such as floods and more importantly against extensive dry spells, i.e., droughts. Recently, global warming and climate change effects increased the frequency and intensity of extreme events, especially floods and droughts. These are well-known, because the anthropogenic activities play significant role in such extremes (IPCC, 2001, 2007, 2013). Accordingly, new methodological approaches are needed for drought severity measurement to take precautions against its destructive consequences (Almazroui et al., 2017; Mohorji et al., 2017). Many researchers sought different methodological droughts assessment among whom are Heim (2002), Redmond (2002), Mishra and Singh (2010) and Vicente-Serrano et al. (2012).

In order to specify the dryness degree McKee et al. (1992, 1995) suggested a simple and straightforward measure under the name of Standardized Precipitation Index (SPI). It is based on the conversion of the underlying probability distribution function (PDF) of a given hydro-meteorological record series into a standardised normal (Gaussian) PDF. Most often two-parameter Gamma PDF is employed for the basic data and then it is transformed to standardised normal (Gaussian) PDF. It can be used for any time duration, annual or monthly, but most often monthly periods are common in the practical applications, because of the agricultural activities' seasonality.

There are other meteorological drought severity measurements such as the Palmer Drought Severity Index (PDSI), which considers dry and wet spells from water balance point of view (Palmer, 1965). Subsequently, PDSI is modified (PMDI) to deal with real-time use. Guttman (1998, 1999) compared PMDI and SPI for a set of time durations starting from monthly basis (Heddinghaus and Sahol, 1991). Finally, they recommended that SPI provides easy and simple use in practice, and therefore, its use can be considered as the primary drought index.

The application of the SPI methodology is not restricted only for precipitation, and it has been used directly or indirectly by many researchers for different hydro-meteorological studies (Hayes, 2000; Lloyd-Hughes and Saunders, 2002; Karavitis et al., 2011; Bonsal et al., 2012). The SPI became widely applied for precipitation dryness classification in many countries and WMO (2012) advised its use officially.

The main purpose of this paper is to suggest that although the SPI is simply and capable to classify the dryness degrees into five sub-classes, but it fails to describe the actual drought characteristics as they are in the original hydro-meteorology records time series. An improved SPI (ISPI) methodology is suggested for actual drought characteristic calculation. Among the drought characteristics drought duration, amount and intensity are very significant quantities, which can be objectively calculated from the original hydro-meteorology series. The application of the ISPI and drought characteristics calculations are presented for Istanbul City, Turkey European side meteorology station monthly precipitation data from 1980 to 2018, inclusive.

2 SPI methodology

In general, drought indices are developed for precipitation, runoff, evapotranspiration and other hydro-meteorological variables to assimilate data to reflect the possibility of dry spell indices. Standard Precipitation Index (SPI) provides classification standards as 'normal dry', 'slightly dry', 'moderate dry', 'very dry', and 'extremely dry'. Hence, a qualitative measure is obtained and it helps decision makers better than the raw data. Although, there are many drought indices in the literature, but the most frequently used one is SPI, which is also recommended by WMO (2012). SPI is suggested first by McKee et al. (1993) based only on monthly precipitation records and then it is used by numerous researches in various applications and also with various versions and modifications. The classical SPI classes are given as in Table 1 for any standardised hydro-meteorology data.

Table 1 SPI drought classes

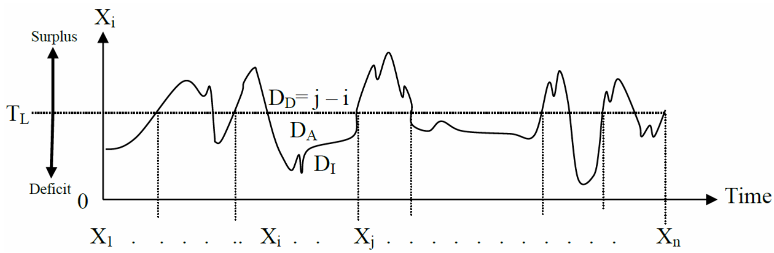
Class	*SPI value*	*Classification*
1	0.00 to –0.50	'Normal dry'
2	–0.50 to –0.99	'Slightly dry'
3	–1.00 to –1.50	'Moderately dry'
4	–1.50 to –2.00	'Very dry'
5	<2	'Extremely dry'

The main idea behind the SPI methodology is first to find the best matching PDF to hydro-meteorology data at hand, and then its conversion to a standard normal (Gaussian) PDF. The classifications in Table 1 are all based on such a standard normal PDF. If SPI is calculated on short time durations then it reflects closely the soil moisture, whereas for long time durations groundwater and reservoir storages are considered. Most often, the hydro-meteorology data are fitted typically to a two-parameter Gamma or three-parameter Gamma (Pearson) PDFs. In order to quantify the effects of each drought type, various indices are suggested in different publications (Gibbs and Maher, 1967; McKee et al., 1993; Narasimhan and Srinivasan, 2005; Palmer, 1965; Steinemann et al., 2005) such as the SPI, Rainfall Anomaly Index (RAI), Decile Index (DI), Drought Area Index (DAI), Surface Humidity Index (SHI), Stream Drought Index (SDI), Soil Moisture Deficit Index (SMDI), Evapotranspiration Deficit Index (ETDI) and PDSI. Drought indices are expected to have universal acceptability, versatility and easy interpretations.

3 ISIS and drought characteristics

The ISIP is based on the probability correspondences of the classical SPI classifications given in Table 1 for the original data PDF. For this purpose, the probability correspondences of the classical SPI levels (0.0, –0.50, –1.00, –1.50 and –2.00) are considered on the original data PDF. Figure 1 represents a hypothetical hydro-meteorology record time series as X_1, X_2, X_3, …, X_n with a threshold level, TL, which may assume any value between the extreme values (maximum and minimum) of given hydro-meteorology time series.

Figure 1 Objective drought quantities



In this figure, TL may represent any classical SPI level probability reflection in the actual data series. In general, it is taken as the arithmetic average in practical applications, but in this paper to compare the results with the classical SPI basic level is adapted, which is 0.0 corresponding to the median value. A given time series and threshold level are enough to define the drought characteristics, because the threshold level divides the whole time series into two groups as surplus and deficit. Those over the threshold level are wet spells (surpluses) and the others less than the threshold level are for dry spells (deficits). Furthermore, within the wet and dry spells, a set of drought characteristics may be defined. Herein, three of them are dry periods (deficit periods), dry amounts and intensities. The following steps provide the quantitative definition of each drought characteristic.

1 For objective drought characteristics identification, preliminarily important features are up- and down-crossing points determinations. Practically, up-crossing number is equal to down-crossing number. For a given time series, the up-crossing (down-crossing) points appear when $X_i > X_T$ ($X_i < X_T$).

2 At i^{th} time instant, a wet spell may occur provided that the hydro-meteorology record is below the threshold level, ($X_i < T_L$). The difference $X_i – T_L < 0$ corresponds to a deficit,

3 A sequence of the above-mentioned uninterrupted sequence of dry spells constitutes a dry duration (length), i.e., and it is limited in the beginning, say at i^{th} instant, and at the end by j^{th} ($j > i$) by wet spells, and hence the dry (deficit) duration (drought duration) is $D_D = j – i$.

4 The summation of all the deficit amounts along a dry period is referred to as the drought amount, DA, which is calculated according to the following expression,

$$D_A = \sum_{k=i}^{j} (T_L - X_K) \quad (X_K < T_L) \tag{1}$$

There are several drought amount values along a given threshold level, and hence, it is possible to search for their PDFs and statistical parameters, if necessary.

5 The drought intensity, D_I, is defined as the drought amount per drought duration, and its mathematical definition is simply as,

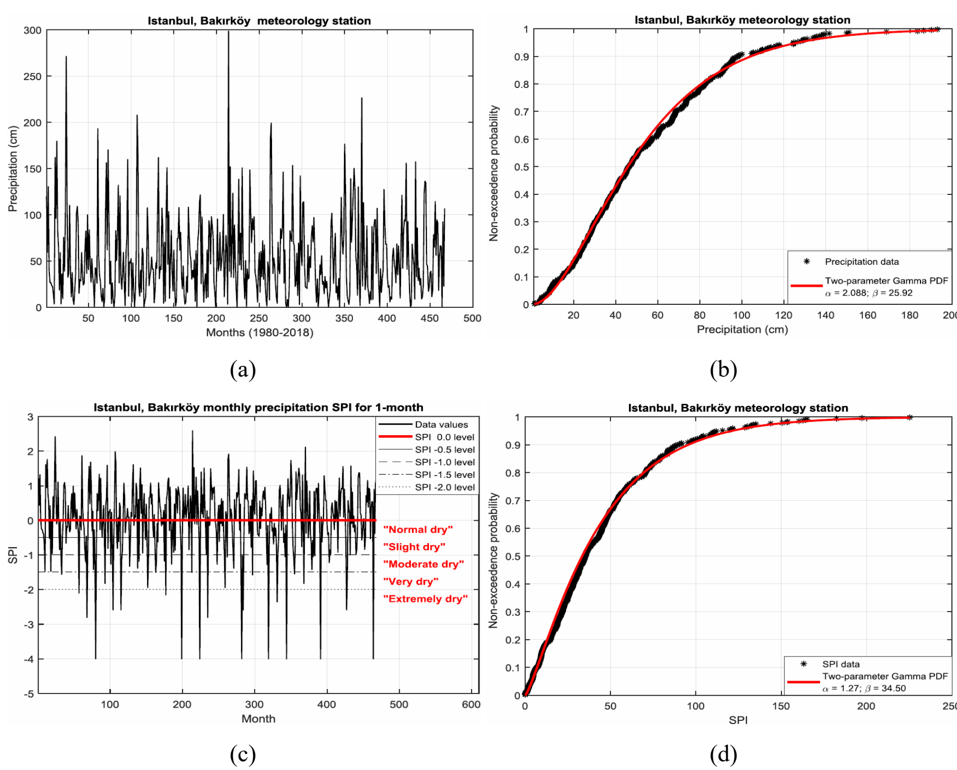
$$D_L = \frac{D_A}{D_D} \tag{2}$$

The drought amount is equal to the area under any drought period as shown in Figure 1. In the following section, only PDFs are taken into consideration for the SPI and drought characteristic comparison purposes.

4 Application

The application of methodology is presented for meteorology station on the European side of Istanbul City at Bakırköy, Turkey, location with its 38 years of monthly precipitation records [Figure 2(a)]. Figure 2(b) presents the empirical non-exceedance probability scatter points, which are in good agreement with the two-parameter Gamma PDF according to chi-square and Kolmogorov-Smirnov tests. The same PDF function is used almost invariably in drought classification systems by SPI procedure. In Figure 2(c), the corresponding SPI one-month graph and the classifications are given for the same meteorology station.

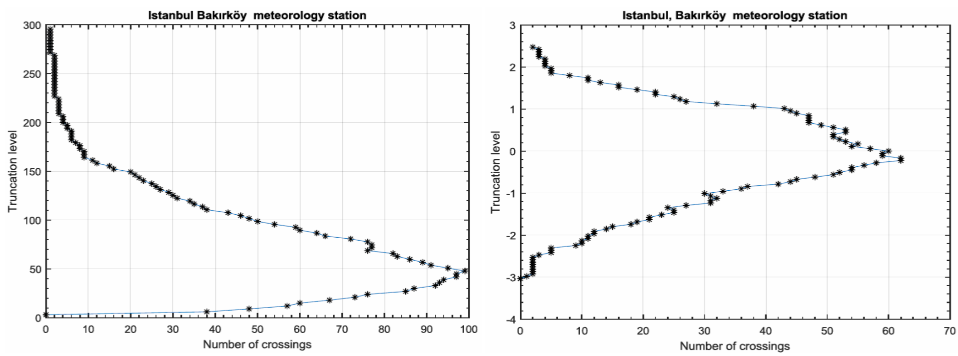
Figure 2 Istanbul Bakırköy meteorology station monthly precipitation, (a) time series records (b) precipitation Gamma PDF (c) SPI one-month graph (d) SPI Gamma PDF (see online version for colours)



Comparison of Figures 2(a) and 2(c) indicates obvious difference between the two time series, although in the former there is bias towards lower values, but there appears a balance in the latter one. The first order serial correlation coefficients are 0.29 and 0.64 for actual precipitation amounts and SPI, respectively, which indicates that SPI destroys the serial correlation coefficient of the original precipitation records.

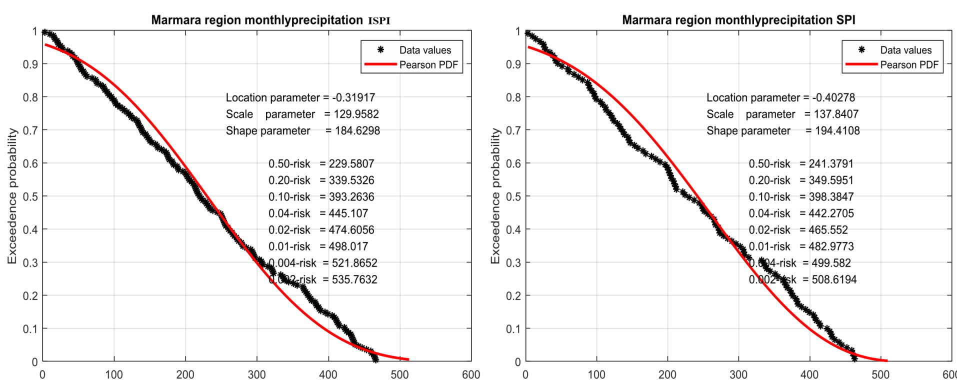
In order to compare the actual precipitation amount with the SPI values, the up-crossing numbers are compared between the two cases in Figure 3. For this purpose, each time series range is divided into a set of truncation (threshold) levels, and the results indicate the relationship between the truncation levels and the up-crossing numbers.

Figure 3 Istanbul Bakırköy meteorology station up-crossing numbers, (a) monthly precipitation data (b) corresponding SPI data (see online version for colours)



(a) (b)

Figure 4 Istanbul, Bakırköy monthly precipitation record crossing numbers (see online version for colours)



These are reflections from the PDFs and they are different from each other, again skewness can be seen clearly in Figure 3(a), whereas Figure 3(b) has more or less symmetric appearance, which is due to the conversion to a standard normal (Gaussian) PDF as a result of classical SPI procedure.

The comparison of the drought characteristics are provided for classical SPI and newly suggested ISPI methods in Figures 4–8 for drought duration, drought amount and drought intensity, respectively. For comparison purposes, corresponding to the SPI graph zero level (statistically arithmetic average median mode) and probabilistically 50% probability median value, in the actual precipitation case ISPI value is equal to 41.75 cm. All the graphs on the left-hand side (on the right-hand side) are for the ISIS (SPI) monthly precipitation records.

Figure 5 Istanbul, Bakırköy monthly precipitation record deficit durations (see online version for colours)

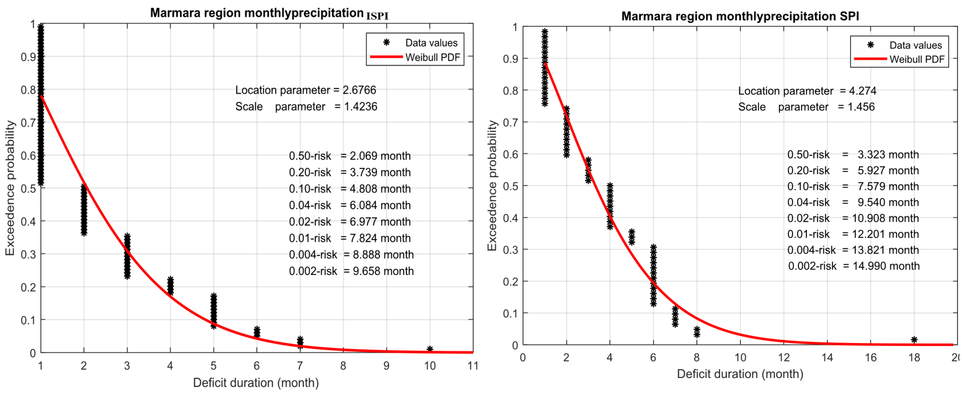
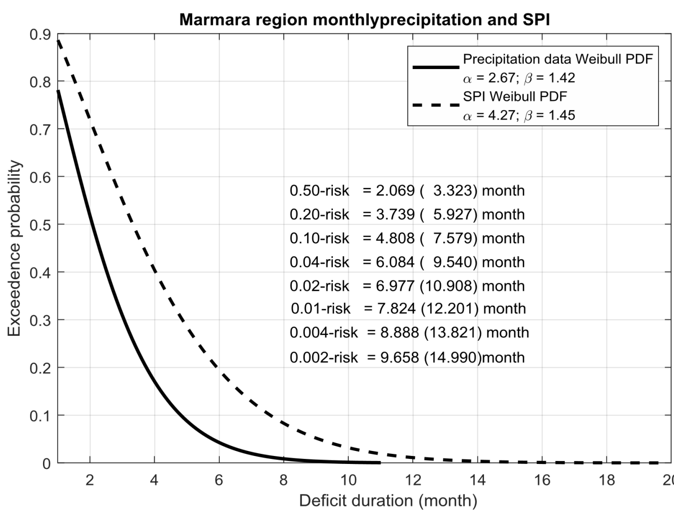


Figure 6 Istanbul, Bakırköy monthly precipitation records and SPI deficit durations



In order to make the difference more obvious, in Figure 6 both drought durations theoretical PDFs are shown on the same graph with SPI risk values in the parentheses. The SPI graph yields over-estimation of actual drought duration, which means that longer drought durations are generated from the transfer of the original PDF to standard normal (Gaussian) PDF.

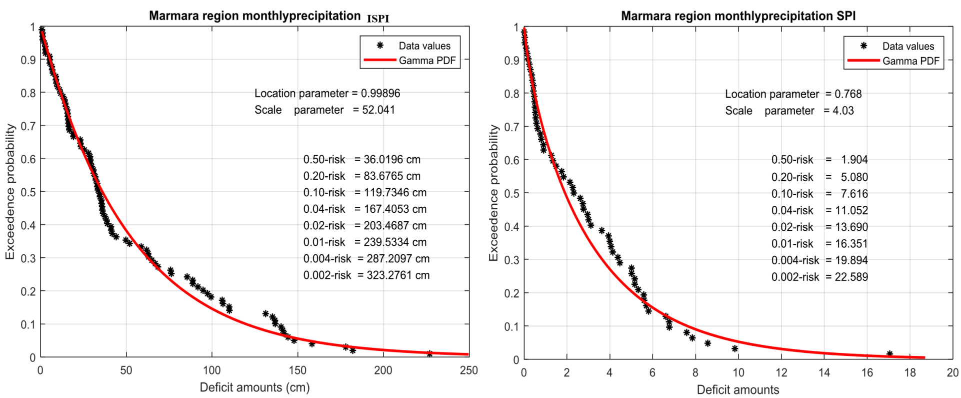
Figure 4 indicates that as for the crossing numbers, in the ISIP and SPI time series, have more or less the same patters, in that they follow three-parameter Gamma (Pearson) PDF with parameters that are practically close to each other. Additionally, in each graph a set of risk levels are given and they are also close within practically acceptable 10%

relative error limits. Hence, as for the crossing number there is no significant numerical difference between the ISPI and SPI time series.

In Figure 5, the appearance of drought durations in two graphs along the 50% truncation level shows significant differences (see Figure 5). They have similar Weibull PDF, but with different parameter values. Especially, drought duration risk levels are very different from each other, and the ISPI values are advised for use in applications, because they come out from the actual data.

Figure 7 presents the empirical and theoretical drought amounts PDFs for ISPI and SPI time series. Again, although the PDFs are of the same type in both cases, but they have widely different parameter and risk values from each other.

Figure 7 Istanbul, Bakırköy monthly precipitation record deficit amounts (see online version for colours)



Finally, drought intensity PDFs are given in Figure 8, which have similar PDFs as three-parameter Gamma (Pearson) PDF again with different parameters.

Figure 8 Istanbul, Bakırköy monthly precipitation record deficit intensities (see online version for colours)

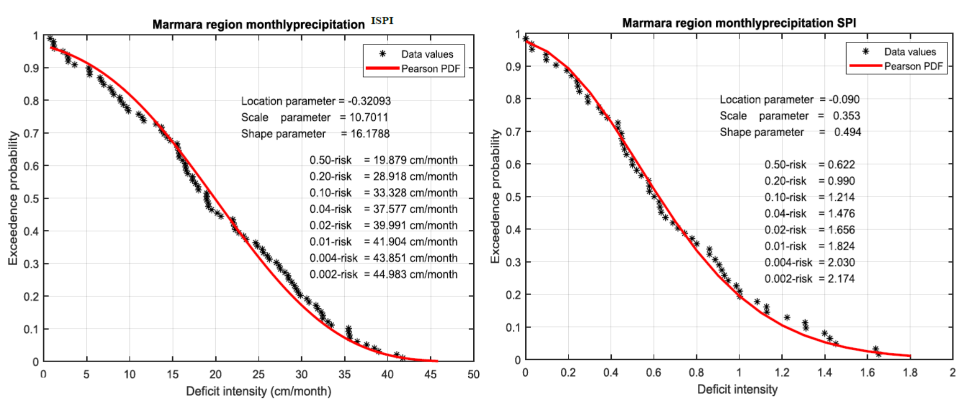


Figure 8 explanations have indicated that although SPI is a simple and useful measure for drought classification, but for drought characteristics actual representation, it needs some adjustment.

5 Conclusions

Dry spells and droughts are very important hydro-meteorological events that affect water resources distribution and management studies. Especially, global warming and climate change effects drive such events to more extreme conditions, and therefore, their objective and fine assessments have significance for mitigation and adaptation studies to reduce the danger of hazards. In the literature, there are two distinctive ways for drought assessments. On the one hand, drought indices help to classify hydro-meteorological records into various classes. For instance, SPI provides five classes as 'normal dry', 'slightly dry', 'moderate dry', 'very dry', and 'extremely dry' categories. Since SPI is the transformation of the original variable PDF to a standard normal (Gaussian) PDF, it cannot reflect the drought characteristics properly among which are drought duration, drought amount and drought intensity. This paper suggests ISPI procedure for drought characteristics calculation and provides a comparative study between the SPI and ISPI. It is concluded that although the classical SPI is useful for standard drought classifications, but cannot reflect actual drought characteristics. The applicative numerical comparative conclusions are presented by considering monthly precipitation records in the European side of Istanbul City, Turkey.

References

Almazroui, M., Saeed, S., Islam, M.N. et al. (2017) 'Assessment of uncertainties in projected temperature and precipitation over the Arabian Peninsula: a comparison between different categories of CMIP3 models', *Earth Syst. Environ.*, Vol. 1, No. 12 [online] https://doi.org/10.1007/s41748-017-0012-z.

Bonsal, B.R., Aider, R., Gachon, P. and Lapp, S. (2012) 'An assessment of Canadian prairie drought: past, present, and future', *Climate Dynamics*, DOI: 10.1007/s00382-012-1422-0.

Gibbs, W.J. and Maher, J.V. (1967) *Rainfall Deciles as Drought Indicators*, Bureau of Meteorology, Bulletin No. 48, 28pp, Commonwealth of Australia, Melbourne.

Guttman, N.B. (1998) 'Comparing the Palmer Drought Index and the Standardized Precipitation Index', *Journal of the American Water Resources Association*, Vol. 34, No. 1, pp.113–112.

Guttman, N.B. (1999) 'Accepting the Standardized Precipitation Index: a calculation algorithm', *Journal of the American Water Resources Association*, Vol. 35, No. 2, pp.311–322.

Hayes, M.J. (2000) 'Revisiting the SPI: clarifying the process', *Drought Network News*, Vol. 12, No. 1, pp.13–14.

Heddinghaus, T.B. and Sahol, P. (1991) 'A review of the Palmer Drought Severity Index and where do we go from here?', *Proc. 7th Conf. on Applied Climatology*, American Meteorological Society, Boston, Massachusetts, 10–13 September, pp.242–246.

Heim Jr., R.R. (2002) 'A review of twentieth century drought indices used in the United States', *Bulletin of the American Meteorological Society*, Vol. 83, No. 8, pp.1149–1165.

IPCC (2001) 'Impacts, adaptation and vulnerability', in McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J. and White, K.S. (Eds.): *Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Vol. 1000, p.2001.

IPCC (2007) *IPCC Fourth Assessment Report Working Group I Report 'The Physical Science Basis'*, Cambridge University Press, New York.

IPCC (2013) 'The physical science basis', *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK.

Karavitis, C.A., Alexandris, S., Tsesmelis, D.E. and Athanasopoulos, G. (2011) 'Application of the Standardized Precipitation Index (SPI) in Greece', *Water*, Vol. 3, No. 3, pp.787–805.

Lloyd-Hughes, B. and Saunders, M.A. (2002) 'Seasonal prediction of European spring precipitation from El Niño-southern oscillation and local sea-surface temperatures', *International Journal of Climatology*, Vol. 22, No. 1, pp.1–14.

McKee, B., Doesken, N.J. and Kleist, N. (1993) 'The relationship of drought frequency and duration to time scales', *Proceeding 8th Applied Meteorology*, Anaheim, CA, 17–22 January, pp.179–184.

McKee, T.B., Doesken, N.J. and Kleist, J. (1995) 'Drought monitoring with multiple time scales', *9th Conference on Applied Climatology*, American Meteorological Society, Dallas, Texas, 5–20 January, pp.233–236.

Mishra, A.K. and Singh, V.P. (2010) 'A review of drought concepts', *Journal of Hydrology*, Vol. 391, Nos. 1–2, pp.202–216.

Mohorji, A.M., Şen, Z. and Almazroui, M. (2017) 'Trend analyses revision and global monthly temperature innovative multi-duration analysis', *Earth Syst. Environ*., Vol. 1, No. 9 [online] https://doi.org/10.1007/s41748-017-0014-x.

Narasimhan, B. and Srinivasan, R. (2005) 'Development and evaluation of Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) for agriculture drought monitoring', *Agricultural and Forest Meteorology*, Vol. 133, Nos. 1–4, pp.69–88.

Palmer, W.C. (1965) *Meteorological Drought*, Res. Paper No. 45, 58pp, Weather Bureau, Washington, DC.

Redmond, K.T. (2002) 'The depiction of drought: a commentary', *Bulletin of the American Meteorological Society*, Vol. 83, pp.1143–1147.

Steinemann, A., Hayes, M.J. and Cavalcanti, L. (2005) 'Drought indicators and triggers'], in Wilhite, D. (Ed.): *Drought and Wilter Crises: Science, Technology, and Management Issues*, Marcel Dekker, NY.

Vicente-Serrano, S.M., Beguería, S., Lorenzo-Lacruz, J., Camarero, J.J. and López-Moreno, J.I. (2012) 'Performance of drought indices for ecological, agricultural, and hydrological applications', *Earth Interactions*, Vol. 16, No. 10, pp.1–27.

World Meteorological Organisation (WMO) (2012) in Svoboda, M., Hayes, M. and Wood, D. (Eds.): *Standardized Precipitation Index, User Guide*, 16pp, WMO-1090, Geneva.