ASSESSING DROUGHT RECURRENCE USING NONLINEAR APPROACH

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REPORT ON THE RESULTS OBTAINED WITHIN THE COORDINATED PROJECTS FOR 2015

Drought is a major natural disaster that can have considerable impacts on society, the environment and the economy. For example, drought in California is considered as a great catastrophe. In Europe alone, the cost of drought over the past three decades has amounted to over 100 billion Euros. By the end of this century, droughts in Europe are expected to be more frequent and intense due to climate change and increased water use (Forzieri, G. et al Hydrol. Earth Syst. Sci., 18, 85–108, 2014). Long-standing result from global-coupled models has been a projected increase in summer drying in the mid-latitudes in a future, warmer climate, with an associated increased likelihood of drought. Summer dryness is expected to increase in the Mediterranean, Central and Southern Europe during the 21st century, leading to enhanced risk of drought, longer dry spells and stronger soil-moisture deficits. According to the" Guidelines for preparation of the Drought Management Plans" (2015. www.gwpcee.org): "Over the past decade, concerns and wide recognition about drought events and water scarcity have grown across the EU. In 2007, the European Commission issued a Communication from the Commission to the European Parliament and the Council - Addressing the challenge of water scarcity and droughts in the European Union (COM (2007) 414 final). In this document, Drought Management Plans (hereinafter DMP) were identified as one of the main policy instruments to combat the problem".

It is presently documented by a number of researches that the mean global surface temperature has increased by about 0.06 degree of Celsius per decade in the 20th century. Essential increase (by 0.19 degree of Celsius) was reported since 70th of last century and it is supposed that the warming is likely to continue. Because of such tendency in the global climate change, drought has become a recurrent phenomenon causing increasing threat and practical damage to society. Presently, in several countries across the globe, along with increase in surface air temperature, erratic and uncertain rainfall distribution especially in arid and semi-arid ecosystems is manifested. Moreover, it becomes more and more obvious that frequently recurring and severe droughts, in nearest future, may become one of most important natural disasters resulting in serious economic, social, and environmental crises.

Therefore because of observed shortening of drought recurrence cycles while the affected area is widening by new parts of territories that were once unaffected, drought forecasting acquires immense importance in the mitigation of possible unwanted impacts. At the same time drought recurrence forecasting can not be possible without purposeful investigation of basics of underlying processes and new tools of nonlinear dynamics for revealing recurrence laws.

In order to find regularities in drought time series and make some predictions it is necessary to analyze their complexity, using such tools as: **Correlation calculations, Recurrent Plots and Recurrent Quantification Analysis, Detrended Fluctuation Analysis, Power Spectrum and Histogram, Lyapunov exponent calculation.**

Let us condider general existing information on the droghts in participant countries:

Georgia: The drought recurrence probability is high enough in Georgia – in some regions it reaches 40%. Droughts occur most notably in the Kakheti, Shida Kartli and Imereti regions. The 2000 drought in Kakheti and Kvemo-Kartli regions affected 696,000 people and caused economic loss of $200 million. In the recent past, drought cycle for Georgia has changed from 15-20 years to 6 years. Over the period 1995 to 2009, droughts inflicted on agriculture reported economic loss of 400 million GEL.

Algeria: Reconstruction of drought severity index for the region from 1456-2002 by analysis of tree ring records show that a single drought year occurred between 12 and 16 times per century, although the number for the 20th century was 19. The most recent drought in Tunisia and Algeria (from 1999-2002) appears to be the worst since the mid-15th century. That's according to researchers who recently analysed tree-ring records from the region. The findings are consistent with predictions from general circulation models of a transition to more arid conditions at mid-latitudes. The recent paper summarizes the data on drougth in Algeria: H. Noureddine et al. Trends of Precipitation and Drought on the Algerian Litoral:Impact on the Water Reserves. Int. Jour. Water Resources and Arid Envir. 1(4): 271-276, 2011

Greece: The short-time drought occurrence in Greece is high – of the order of 1 per year. From the estimation of the SPI on 3- , 6- and 12-months time scales shows that the frequency of mild and moderate drought conditions is approximately of the same order of magnitude over the whole Greek territory. On 6- and 12-months time scales it was found that in almost all cases and for both time scales, the persistence is statistically significant.

Turkey: As a semi-arid country, Turkey is already familiar with this concept. It went through extremely dry periods in the years 1928-1930, 1950-1951, 1973-1974, 1988-1989, 1994-1996, 2000-2001 and 2006-2008.1 The official figures point at a significant increase in not only the frequency, but also the intensity of droughts in the country,2 and with global climate change affecting the Mediterranean basin in particular, it seems even drier days await Turkey.

Contribution of GHHD, Tbilisi

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The 100 years data on daily temperature and precipitation in Tbilisi meteo-station has been obtained and formatted. Traditionally, statistical models have been used for drought forecasting based on linear time series analysis methods. E.g. simple regression and autoregressive moving average (ARMA) are typical models on which drought related statistical time series analysis and drought forecasting is based. However, basically linear models assume that data are stationary, and practically do not enable to deal with non-stationarities and nonlinearities in related natural processes. Therefore it becomes understandable that alternative models and approaches should be used when nonlinearity and nonstationarity play a significant role in the forecasting of drought recurrence. In general, recurrence phenomenon is one of the most important features of complex dynamical systems which helps to understand their spatial and temporal behavior and thus to predict or even control systems behavior. At present there are already developed special data analysis methods enabling to reveal hidden recurrent properties in nonstationary noise systems which look completely random. Based on the above mentioned, the main objective of proposed research is to investigate features of drought recurrence on local scale spatial and temporal scales based on available weather variation data sets. Exactly, general objective is to carry out analysis of nonlinear and recurrence properties of min, max and average air temperature data sets. Special attention will be paid to data sets from weather stations located in areas where for last decade recurring droughts have been observed. All this activity allow to assess drought recurrence characteristics (persistence, return period, etc).

In order to assess drought occurrence it is necessary to have a definition of drought.

According to existing definitions, if the weather pattern lasts a short time (say, a few weeks or a couple months), the drought is considered *short-term*. But if the weather or atmospheric circulation pattern becomes entrenched and the precipitation deficits last for several months to several years, the drought is considered to be a *long-term* drought.

Widely accepted is the Standardized Precipitation Index (SPI) - a probability index that considers only precipitation. The SPI is an index based on the probability of recording a given amount of precipitation, and the probabilities are standardized so that an index of zero indicates the median precipitation amount (half of the historical precipitation amounts are below the median, and half are above the median). The index is negative for drought, and positive for wet conditions. As the dry or wet conditions become more severe, the index becomes more negative or positive.

As the nonlinear analysis is very demanding to the length and quality of the input data, in following only two meteorological temperature time series (Tbilisi and Athens) are considered as good enough.

Thus, our assessment of the recurrence of droughts is based only on temperature data.

In following the joint analysis of both - temperature and precipitation - time series is desirable.

The program package Drought Assessment Package Application (DAP APP) is compiled

Program package presents easy-to use friendly toolbox working with time series. Application is designed to work with TXT or DAT files which contain for example temperature or precipitation measures. Input files should have only one column.

This package includes different popular instruments for data analysis:

1. **Recurrent Plots (RECURRENCE PLOT tab menu) and Recurrent Quantification Analysis (RQA)**
2. **Detrended Fluctuation Analysis (DFA tab menu);**
3. **Power Spectrum and Histogram (HISTOGRAM/POWER SPECTRUM tab menu);**
4. **Correlation calculation (CORRELATION DIM/AUTOCORRELATION tab menu);**
5. **Lyapunov exponent calculation (LYAPUNOV EXPONENT tab menu);**
6. **Stationary test (STATIONARY TEST);**

The package includes Tbilisi Temperature daily series, Tbilisi Max Temperature (Tmax) summer period series, Duration (in days) of period with Tmax>30 C^o series, Symbolic Tmax daily series (description is on the page 5 after Fig.7). All listed below applications are realized on the Tbilisi data.

The full description of the Package (DAP APP Guide.15.10.15) is attached (Annex 1).

Here we show only the results on the recurrence of the droughts defined as days with temperature higher then 30^{0}C of various durations (Fig.1). We took only summer month from Tmax daily series and calculated duration of droughts (in days) with max temperature (Tmax) higher than 30 C^o in summer months. In the result we get Tmax duration series versus period number, which is depicted on the Fig.1. Note, that the number of periods with Tmax higher than 30 C^o are not uniform - so the X-axis shows only the number of high temperature period, which can contain m = 2, 5, 10,...... days.

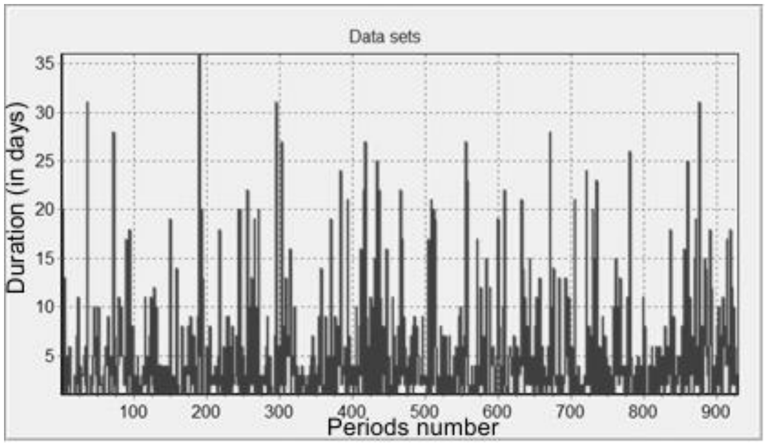
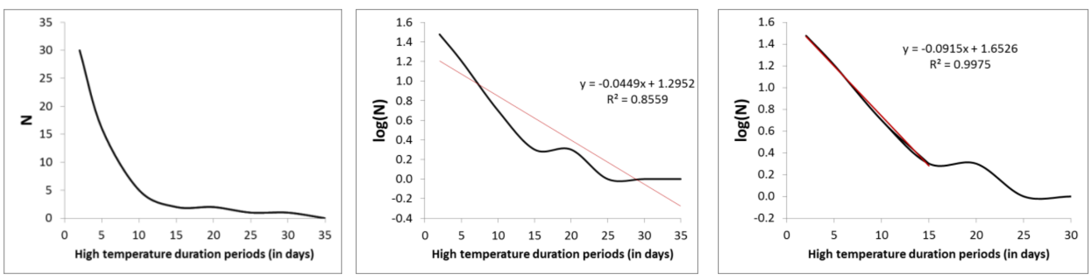


Fig.1. Duration of periods with Tmax higher 30 C^o versus period number of period with Tmax higher than 30 C^o, which can contain *m* = 2, 5,10,...... days.



a. b. c.

Fig. 2. Frequency-Intensity Estimate Plot: a) linear plot of number of droughts N in five years (i.e. drought rate) with duration more than 2 days versus corresponding durations (intensity of droughts); b) the same in semilog scale - log N versus intensity with straight line approximation for all intensities; c) the same as 7 b with straight line approximation for intensities from 2 to 15 days.

Frequency-Intensity Estimate Plot or plot of number *N* of droughts in 5 years (i.e. drought rate) with duration *m* more than 2, 5, 10, 15, 20, 25, 30, 35 days versus corresponding durations (intensity of droughts (Fig.2 a, b, c) of high-temperature periods was done on duration series (Fig. 1). It manifests the presence of heavy-tail i.e. different statistics for extreme events (long droughts) with duration larger than 15 days (Fig. 2 a). We observe that up to period length equal to 15 days, relationship between occurrence of high-temperature periods and period lengths is very well approximated by exponential function (Fig. 2 c) and recurrence time T_R can be accessed accurately for 15-days droughts. For example, 15 days drought reoccur as (antilog(log0.3))/5 (1/year) ≈ 2/5≈ 0.4 (1/year) or T_R = once per two and a half years. The linear approximation for a whole semilog plot (Fig. 2 b) is much less accurate and for 15 days drought reoccurrence we get (antilog(log0.6))/5 (1/year) ≈ 4/5 ≈ 0.8 (1/year) or T_R ≈ once per year and for droughts with duration 35 days ((antilog(log(-0.35)))/5 (1/year) ≈0.45/5 (1/year) =0.09 /5 (1/year) ≈ 0.1 (1/year) or T_R ≈ once per ten years, which is less than observed data. According to observed data ((antilog(log(0)))/5 (1/year) ≈ 1/5 (1/year) or T_R ≈ once per five years.

The analysis shows that for hard droughts approximation we need to use special statistics (Humbel, etc).

Contribution of ECFF, Athens

The problem of droughts in Greece was considered in several works using traditional approaches, for example, Standardized Precipitation Index (SPI) (see: I. Livada and V. D. Assimakopoulos. Spatial and temporal analysis of drought in Greece using the Standardized Precipitation Index (SPI), Theor. Appl. Climatol. 89, 143–153, 2007), or the Palmer Drought Severity Index (PDSI), (see: N.R. Dalezios et al. Severity-duration-frequency analysis of droughts and wet periods in Greece. Hydrological Sciences-Journal, 2000, 45(5) October, 751-769; A. Loukas et al. Hydroclimatic Variability of Regional Droughts in Greece Using the Palmer Moisture Anomaly Index, Nordic Hydrology, 33 (5), 2002,425-442).

For nonlinear analysis National Observatory of Athens collected historical climatic data of daily maximum air temperature (Tmax) and daily sums of precipitation for Greece. To meet the criteria of long-term time series adequate for climatic research and optimal spatial coverage of the Greek domain, 10 stations were selected (Table 1). The complex morphology of Greece (including horography, proximity to the sea, islands, intense urbanization etc) introduces a variety of different climatic components and the existence of quite local climates in the country. Selection criteria included consideration of these particular features of Greek complex morphology and aimed to represent areas of different climatic properties and discriminate between continental/coastal/marine sites.

The selected climatic series come from the network of the Hellenic National Meteorological Service (HNMS) which actually initiated and expanded its operation during the 1950's, providing long term climatic data for several parts of Greece. Some of the records are available until now (2013) and some others until the early 2000's, depending on the ongoing quality controls carried out at the HNMS. However, the climatic series ensure an adequate length for climatic analysis.

As for Athens, the time series is selected from the historical archives of the National Observatory of Athens and span a period of more than one century.

Actually, the National Observatory of Athens (NOA) (founded in 1842) holds the oldest climatic records in Greece which constitute a unique source of climatic information for a broader area of southeastern Europe. These records concern a large number of climatic variables, including daily and sub-daily measurements of air temperature and precipitation. Although data for Athens go back to the mid 19th century, the historical station was permanently established at its current position during the late 19th century. Hence, the time series for Athens concern the period 1897-2013.

The names of the selected stations as well as their coordinates and available periods for analysis are shown in the following Table.

Table 1: Selected stations along with their coordinated and available period for analysis.

Station Name	Latitude(Deg:min)	Longitude(deg:min)	Altitude (a.s.l) m	Period
NOA (Athens)	**+37:58**	**+23:43**	**107**	**1897-2013**
Alexandroupolis	+40:51	+25:26	3.5	1955-2005
Herakleion	+35 :20	+25 :11	39	1955-2013
Larissa	+39 :39	+22 :27	74	1955-2013
Florina	+40 :47	+21 :24	662	1961-2008
Chania	+35:30	+24:02	150	1958-2013
Methoni	+36:50	+21:42	52	1955-2013
Rhodes	+36:24	+28:05	11	1955-2013
Kozani	+40:17	+21:47	626	1955-2013
Corfu	+39:37	+19:55	11	1955-2013

Daily precipitation sums are provided in mm and maximum daily air temperature in ^{0} C.

Contribution of CRSTRA, Algeria

CRSTRA has sent in 2014 the data on the temperature and precipitation from 10 stations.

Adrar	27°49	00°11W	279
Bechar	31°38	02°15W	807
Biskra	34°48	05°44E	82
Bordj Badji Mokhtar	21°12	00°34E	397
Djanet	24°16	09°28E	970

Ghardaia	32°24	03°48E	468
In Salah	27°14	02°30E	268
Ouargla	31°55	05°24E	139
Tamanrasset	22°49	05°27E	1362
Tindouf	27°42	08°10W	443

Unfortunately, the data sets are too short for reliable nonlinear analysis - all of them begin in 1988.

Contribution of ECMHT, Baku

ECMHT has sent in 2014 the data on the precipitation from 14 stations.from 1999 to 2013

Unfortunately, the data sets are too short for reliable nonlinear analysis - all of them begin in 1999. Besides, on this stage of research we analyze only temperature time series.

Finally, only data from Georgia, (Tbilisi) and Greece (Athens) correspond to the reliable nonlinear analysis conditions.

Contribution of AFEM, Ankara

Colleagues from AFEM send us the report"Drougths in Turkey",compiled by by Levent Kurnaz - see Annex 2 (ipc.sabanciuniv.edu). A variety of meteorological data and drought indices indicate that after going through a drought in 2007-2008, Turkey is now experiencing a significant meteorological drought in 2013-2014. The drought we are currently experiencing is progressing from a meteorological drought to an agricultural and hydrological drought due to the significant drop in winter precipitation. Because of imminent climate change, these droughts are expected to change in the long term from simply being a periodic natural event to becoming part of daily life. As a result, it is necessary not only make plans for Turkey's drinking water, but also shift the demand for hydroelectric energy to alternative energy generation systems that can handle the reduction in precipitation as well as bring agricultural irrigation methods in line with drought conditions.

The report presents results, obtained by traditional commonly-used drought indices used around the world today include the Standardized Precipitation Index (SPI), the Normalized Precipitation Anomaly Index (NPAI), the Palmer Drought Severity Index (PDSI), and rainfall deciles.

At the same time AFEM has not sent to us the temperature/precipitation numerical time series from Turkey, so it was impossible to apply our program package for nonlinear analysis of drought recurrence.

The main deliverables of the project are:

i. The package of programs for nonlinear analysis of time series **Drought Assessment Package Application (DAP APP)**, which is very user-friendly and allows to calculate many nonlinear characteristics of the temperature time series (see Annex 1);

ii. Nonlinear analysis of recurrence of droughts of various durations in Tbilisi area (Georgia) and Athens is presented (Annex 1.2). The calculations of Standardized Precipitation Index (SPI) is also presented (Annex 3). Frequency-Intensity Estimate plot or plot of number *N* of droughts with duration *m* more than 2, 5, 10, 15, 20, 25, 30, 35 days versus corresponding manifests the presence of heavy-tail i.e. different statistics for extreme events (long droughts) with duration larger than 15 days. We observe that up to period length equal to 15 days, relationship between occurrence of high-temperature periods and period lengths is very well approximated by exponential function and recurrence time T_R can be accessed accurately for 15-days droughts. For example, 15 days drought reoccur with T_R = once per two years. Assessment of recurrence period T_R for the droughts with duration 35 days and more are less accurate ($T_R \approx$ once per four years).