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Statistical analyses of extreme rainfall events in Thessaloniki, Greece

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ABSTRACT

Concern about climate change has amplified the need for accurate information about variations in statistical characteristics of extreme rainfall events in both smaller temporal and spatial scale. For this reason, in this paper the hourly precipitation measurements obtained at the Department of Meteorology and Climatology of the Aristotle University of Thessaloniki meteorological station, during the period 1947–2003, are used. A new threshold determining method is proposed, in order to define the extreme rainfall event in Thessaloniki, based upon the polynomial trends of the cumulative distribution functions, retrieved from hourly precipitation measurements. Through this approach, three statistical goodness-of-fit tests were carried out, in order to come up with the best fitting probability distributions, for annual and seasonal extreme precipitation conditions. Based upon this fitting distribution procedure, return periods for different precipitation extreme values were calculated. Results indicate that the value of 6.5 mm/h is the hourly threshold of extreme precipitation in Thessaloniki over the studied period. Furthermore, the Generalized Pareto, and the Johnson SB, the log-Gamma and the Lognormal are the best fitted probability models for the description of annual and seasonal extreme rainfall events, respectively. Last but not least, the contribution of hourly data in the accuracy of the results is discussed.

1. Introduction

According to the IPCC reports (2007), the global warming, that is derived from the positive concentrations of greenhouse gases, has a possible influence on the global hydrological cycle. Characteristically, Trenberth (1999) observed that the increased ultraviolet radiation that is produced by the greenhouse effect, contributes on a further increase of evaporation. This results in the strengthening of the atmosphere's capacity to hold water vapor in hot days, which in its turn causes intensification of the hydrological cycle and increase of the frequency of extreme rainfall events. Therefore, changes that will potentially happen in the distribution of extreme precipitation are crucial and of a great research interest, due to its enormous impact on humans, their properties, and the environment.

A lot of scientific work has already been done worldwide on the subjects related to the probability distributions of extreme precipitation. As it is expected, the outcomes vary according to the objective, methodology, study area and database of each study. For example, Zalina et al. (2002) reported that the Generalized Extreme Value (GEV) shows very good descriptive and predictive abilities of the annual extreme rainfall series in Peninsular Malaysia, while Koutsoyiannis (2004) concluded that neither of the two-parameter special cases of the GEV distribution (Gumbel and Frechet ones) is appropriate for modeling the annual maximum rainfall series in Europe and USA. Analogous studies have been performed at several single sites all over the world (Hirose, 1994; Nadarajah and Withers, 2001; Chu et al., 2009), as the geographical characteristics of the studied area affect substantially the spatial variability of extreme precipitation events. These studies play a significant role in the prevention of the flood damage caused by extreme rainfall events, since they are considered to be invaluable tools for the construction of certain projects, such as drainage systems and dams.

Although bibliography seems to be extensive on the studies of extreme precipitation (Bocheva et al., 2009; Müller et al., 2009; Xu et al., 2011; Fernández-Montes et al., 2014; Santos and Fragoso, 2013; Song et al., 2015; Gao et al., 2016), very few researchers examined the statistical analyses of extreme rainfall conditions by using hourly precipitation measurements (Winkler, 1992; Kanae et al., 2004; Fujibe et al., 2005; Sen, 2008; Twardosz, 2010; Lenderink et al., 2011). This could be attributed to the rarity of these data. However, the validity of the results of the statistical analyses could be improved through the study of the extreme rainfall events in a smaller temporal scale than daily. The utilization of hourly records is more beneficial, as the heavy precipitation events occurring mainly in the warm period of the year, are characterized by their short duration. In Greece, the studies using hourly precipitation measurements are limited. Particularly, in Thessaloniki the investigation of the diurnal rainfall pattern is the unique example of using hourly rainfall data and was carried out by Giles and

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Flocas (1990).

As far as the definition of extreme precipitation is concerned, both parametric and non-parametric statistical techniques are usually adopted, in order to identify the rainfall threshold above which a precipitation event can be characterized as an extreme one. Feng et al. (2007) were the first researchers who have applied the Block Maxima method for the modeling of annual extreme rainfall in China. In addition, the Peak over Threshold method was proposed by Anagnostopoulou and Tolika (2010 and 2012), as the best parametric approach for the fitting of a statistical distribution to the tails of an unknown distribution. On the other hand, the absolute threshold of 60 mm/day was used by Karagiannidis et al. (2012), in order to investigate the climatological aspects of extreme precipitation related to mid-latitude cyclonic systems in Europe. In a similar approach to the problem, Bocheva et al. (2010) adopted the threshold of 100 mm/day for the climatic analysis of the torrential precipitation in Bulgaria. In the present study, the selection of a fixed absolute threshold is deemed to be the most appropriate and efficient technique, as it could contribute significantly to the understanding of the impact of extreme rainfalls on society in local scales.

The purpose of this study is to define the most representative absolute hourly threshold of extreme precipitation events in Thessaloniki. The determination was succeeded through a new proposed method based on the coefficients of the independent variables of the polynomial regression lines of the cumulative probability distributions of some data sets, created from hourly rainfall records. Utilizing the hourly precipitation measurements of the meteorological station of the Department of Meteorology and Climatology of the Aristotle University of Thessaloniki, covering a 57-year period, the best fitted probability distributions were identified on both, annual and seasonal scale, as well as, the return levels of some of the most extreme rainfall events were calculated.

In Section 2, a detailed description of both the materials and the methodology used, is provided. The analyses of the results for the determination of the fixed hourly threshold of extreme rainfall in Thessaloniki is provided in Section 3. Moreover, the outcomes of the best fitted distributions of extreme precipitation in the studied area are discussed in this section. The conclusions are drawn in Section 4.

2. Materials and methodology

2.1. Study area and data

Thessaloniki (40° 37′ N, 22° 95′ E) is the capital of the region of Macedonia in Northern Greece, as well as, the second largest city in the country (Fig. 1a). The city is situated at the heart of Thermaikos gulf in the Northern Aegean Sea. The climate of the area is a typical Mediterranean mild climate with bimodal seasonal variation of precipitation. According to Köppen classification, it is characterized as Csa. The principal maximum and minimum are observed in December and August, respectively. The mean annual precipitation and its standard deviation is: 451.7 mm ± 96.3 mm, according to Stathis and Mavromatis (2009), for the period 1930–2004 and 475.6 mm ± 105.4 mm, according to Pakalidou and Karacosta (2016), for the much longer period of 1892–2015.

The data used in this study are the only available hourly measurements of precipitation obtained at the Meteorological Station of the Department of Meteorology and Climatology of the Aristotle University of Thessaloniki (AUTH) for the period 1947–2003. Stathis and Mavromatis (2009), by applying the Bartlett's test of homogeneity, examined the homogeneity of precipitation measurements at Thessaloniki, for a little longer period (1930–2004), using monthly, seasonal and annual precipitation measurements. The results suggest that AUTH has exhibited great precipitation homogeneity, which could be attributed to the unchanged position since 1930. As far as the investigation of the randomness of the examined time series of precipitation is concerned, they concluded that non-randomness is present in the data in accordance with the Cramer's test.

2.2. The definition of the hourly threshold of extreme rainfall in Thessaloniki

According to the Glossary of Meteorology (Huschke, 1959), precipitation is characterized as heavy, when its intensity exceeds 7.62 mm/h. Based upon this indication, a set of ten (10) candidate thresholds {*3.5 mm/h, 4.0 mm/h, 4.5 mm/h, 5.0 mm/h, 5.5 mm/h, 6.0 mm/h, 6.5 mm/h, 7.0 mm/h, 7.5 mm/h, 8.0 mm/h*} was adopted, aiming at the selection of the most proper and representative hourly threshold of extreme precipitation events in Thessaloniki, during the studied period.

Taking into consideration the aforementioned set of data, *the daily rainfall for each candidate threshold is defined as the highest hourly value that exceeds the i-candidate threshold over a 24-h period, where $i = 1, \ldots, 10$*. The daily rainfall of the days with hourly measurement less than the i-candidate threshold is considered to be 0. As a consequence, ten (10) sets of data information were constructed (one for each candidate threshold), which contain the daily rainfall values of the period 1947–2003. Having explained what is meant by daily rainfall values in the particular study, *the daily extreme rainfall values are defined as the no zero daily rainfall ones for each set of information*. The reconstructed sets of data information, which now contain the daily extreme rainfall values of the studied period, were fully described by the best-fitted extreme value theoretical distributions according to Kolmogorov-Smirnov goodness-of-fit test.

In the following two sub-sessions of this paragraph, the procedure followed for the definition of the hourly threshold of extreme rainfall in the studied area over the period 1947–2003 was described visually and deterministically. Moreover, a schematic overview of the aforementioned procedure is demonstrated in Fig. 1b

2.2.1. Visual definition of the hourly threshold of extreme rainfall in Thessaloniki

The visual identification of the hourly threshold of extreme precipitation in Thessaloniki was achieved by the illustration of the aforementioned ten (10) cumulative distributions in a figure. The use of the cumulative distributions for each candidate set is attributed to the fact that they are better comparable than the probability density functions according to Reimann et al. (2005), and from the theoretical point of view, the cumulative distributions usually provide a more comprehensive and thorough picture of the function itself. In addition, the slope of the cumulative distribution of "extreme hourly rainfall" of Thessaloniki should tend to differ from the other ones. Specifically, a potential sudden change in the slope between the successive cumulative curves indicates the most appropriate hourly threshold of extreme rainfall over the studied period.

2.2.2. Deterministic definition of the hourly threshold of extreme rainfall in Thessaloniki

In order to increase the reliability of the hourly threshold that was selected with the visual method in Section 2.2.1, the use of a more objective procedure is deemed necessary. The key-steps can be listed as follows:

a) Firstly, the 3rd order polynomial trendlines of the cumulative distributions for each candidate threshold were calculated, as the coefficients of their independent variables are able to define