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A regional GEV scale-invariant framework for Intensity–Duration–Frequency analysis

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SUMMARY

We propose in this paper a regional formulation of Intensity–Duration–Frequency curves of point-rainfall maxima in a scale-invariant Generalized Extreme Value (GEV) framework. The two assumptions we make is that extreme daily rainfall is GEV-distributed – which is justified by Extreme Value Theory (EVT) – and that extremes of aggregated daily rainfall follow simple-scaling relationships. Following these assumptions, we develop in a unified way a GEV simple-scaling model for extremes of aggregated daily rainfall over the range of durations where scaling applies. Then we propose a way of correcting this model for measurement frequency, giving a new GEV-scaling model for extremes of aggregated hourly rainfall. This model deviates from the simple-scaling assumption. This framework is applied to the Mediterranean region of Cévennes-Vivarais, France. A network of about 300 daily raingage stations covering the last 50 years and accumulated to span the range 1 day–1 week is used to fit the scale invariant GEV-model locally. By means of spatial interpolation of the model parameters, and correction for measurement frequency, we are able to build a regional model with good performances down to 1 h duration, even though only one hourly station is used to build the model. Finally we produce mean and return level maps within the region in the range 1 h–1 week and comment on the potential rain storms leading to these maps.

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1. Introduction

Assessing the occurrence of extreme hydrometeorological events can only be solved by analyzing very-long stationary data series. Long-term rainfall series are usually available at local scale through records integrating rainfall over daily or longer periods. In such a case, direct assessment of the frequency of sub-daily events is impossible. This issue can be overcome by considering Intensity–Duration–Frequency (IDF) relationships. A formula of IDF curves involving an empirical formulation of scaling is provided in Koutsoyiannis et al. (1998). In the 90s fractal science provides a more theoretical framework to address scaling issues in rainfall through the concept of scale invariance (Schertzer and Lovejoy, 1987; Ladoy et al., 1993; Marsan et al., 1996; Venugopal et al., 1999; Deidda et al., 1999; Harris et al., 2001). Scale invariance applied to extreme rainfall implies that the statistical properties of extreme rainfall over different time scales are related to each other by an operator involving only the scale ratio and the scaling exponent. From a higher aggregation level it is thus possible to infer the statistical properties of the process at finer resolutions, and in particular to estimate IDF curves at durations for which no data are available. Burlando and Rosso (1996) first demonstrated that the IDF relationships commonly used in practice were actually expressions of rainfall scale invariance. Since then, many studies dealt with scale invariance in extreme rainfall. The statistical framework was first built around classical distributions for large values, mainly lognormal (Burlando and Rosso, 1996; De Michele et al., 2011), Levy-stable (Menabde and Sivapalan, 2000) and Gumbel (Menabde et al., 1999) distributions. Few studies (Nguyen et al., 1998; Bougadis and Adamowski, 2006) proposed IDF formulations for annual maximum intensities under the Generalized Extreme Value (GEV) distribution. A unified mathematical formulation of simple-scaling for rainfall maxima is given in Koutsoyiannis et al. (1998) under a variety of distributions. It is extended in Van de Vyver and Demarée (2010) for peaks-over-threshold. All the aforementioned studies were applied locally, i.e. on one or very few stations, without any regional view. The first comprehensive regional studies of scaling in maximum rainfall were made by Yu et al. (2004) and Borga et al. (2005) under the assumption of Gumbel distribution.

In the meantime, emergence of extreme value theory revealed that GEV distribution, of which the Gumbel distribution is a

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particular – light-tailed – case, is the well-founded distribution for maxima (Coles, 2001; Katz et al., 2002). During years, the Gumbel distribution has been by far the most popular model for modeling extreme rainfall. Yet, recent studies (e.g. Coles et al. (2003), Koutsoyiannis (2004a,b), Papalexiou and Koutsoyiannis (2013)) showed that rainfall maxima may exhibit thicker tails than that of a Gumbel distribution. Therefore the GEV distribution might be a better choice. A previous study (Ceresetti et al., 2010) revealed that this is indeed the case in the studied region. Yet, despite the regional study of Borga et al. (2005) in the Gumbel case, there is to the best of our knowledge no regional study of simple-scaling of extreme rainfall in the GEV case. Nguyen et al. (1998) and Bougadis and Adamowski (2006) proposed the basement for a formulation of IDF curves in the GEV framework. However their analysis remains local and the final computation of IDF curves requires the combination of different equations, which may complicate their practical implementation. In addition, both studies consider a unique GEV scaling model for rainfall maxima corresponding to different measurement frequencies, although extreme value theory shows that this implies a modification of the GEV distributions (Robinson and Tawn, 2000). Muller et al. (2008) use this result in a scaling framework but in a local study and for two durations only.

The purpose of this article is to unify and extend the works of Nguyen et al. (1998), Borga et al. (2005), Bougadis and Adamowski (2006) and Muller et al. (2008) by proposing an integrated derivation of IDF relationships in the context of GEV-distributed maxima. We innovate in two ways. First, the theoretical framework is for the first time extensively validated at regional scale. Second, we build a model that is valid at sub- to multi-daily scales even though it requires only daily raingage data – which are usually abundant – to be fitted. A correction for measurement frequency is applied to this purpose, giving a new GEV-scaling model that deviates from the simple-scaling assumption. Two corrections are compared: the first one is due to extreme value theory (Robinson and Tawn, 2000) while the second one follows the frequency factor method of Hershfield (1962). The application is carried out on about 400 daily and 60 hourly raingage records over a $200 \times 200\ \mathrm{km}^2$ region, which allows us to highlight and discuss regional properties of IDF relationships.

The paper is organized as follows. Section 2 recalls the classical expressions of Intensity–Duration–Frequency curves and scale-invariance assumption. Section 3 provides expression of simple-scaling in the GEV case. Section 4 presents the data and gives evidence of simple-scaling in the study region. The GEV scale-invariant model is applied to intensity maxima of daily rainfall aggregated between 1 day and 1 week. By means of spatial interpolation of the model parameters, a regional model for IDF curves is obtained. In Section 5 the model is validated at multi-daily scales on daily validation stations and two corrections of the model for measurement frequency are compared for scales between 1 h and 1 week. Finally Section 6 provides a phenomenological discussion of return level maps at sub- and multi-daily scales. Section 7 gives conclusion of this study.

2. Intensity–Duration–Frequency curves and scale-invariance

Intensity–Duration–Frequency (IDF) curves are functions of the form $i(D, T_R)$ relating the rainfall intensity quantiles i with the duration D and the frequency of occurrence F otherwise expressed in terms of return period $T_R = (1-F)^{-1}$. Empirical IDF curves are usually a special form of the generalized formula (Koutsoyiannis et al., 1998):

$$i(D, T_R) = a(T_R)(D+\theta)^{-H}, \tag{1}$$

where $a(T_R)$ is a function of T_R and H, θ are non-negative coefficients with $H \leqslant 1$. Eq. (1) expresses that rainfall intensity decreases when duration increases, for a given return period. It has the advantage of a separable functional dependence of i on T_R and D. Eq. (1) is equivalent to considering that IDF curves at two durations D and D_0 are linked through:

$$i(D, T_R) = \left(\frac{D+\theta}{D_0+\theta}\right)^{-H} i(D_0, T_R). \tag{2}$$

Back to probability, the analog of Eq. (2) for the random variable I_D of maximum rainfall intensity at duration D (mm/h), is

$$I_D \overset{d}{=} \left(\frac{D+\theta}{D_0+\theta}\right)^{-H} I_{D_0}, \tag{3}$$

where $\overset{d}{=}$ is the equality in distribution. The particular case when $\theta = 0$ corresponds to the hypothesis of strict sense scaling:

$$I_D \overset{d}{=} \left(\frac{D}{D_0}\right)^{-H} I_{D_0}, \tag{4}$$

under which moments of order q at durations D and D_0 are linked through:

$$E[I_D^q] = \left(\frac{D}{D_0}\right)^{-Hq} E[I_{D_0}^q]. \tag{5}$$

In the rest of this article, unless specified, model of Eq. (4) is considered. The reason for imposing $\theta = 0$ will be justified in Section 5.2.

3. GEV simple-scaling IDF model

The previous section showed that simple-scaling implies that return levels at any duration D are just scaled functions of return levels at some reference duration D_0 (Eq. (2) with $\theta = 0$). To get those latter return levels, one needs to choose some probability density function for maximum rainfall intensity at the reference duration. We review in this section the choice of the GEV distribution, which is theoretically-founded for modeling of extremes, leading to the so-called GEV simple-scaling model. Such model was previously used in Nguyen et al. (1998) and Bougadis and Adamowski (2006) for the GEV case and Borga et al. (2005) for the particular case of a Gumbel distribution. This framework allows us to derive hereafter an integrated formulation of IDF curves.

The GEV simple-scaling model relies on only two assumptions: first that Eq. (4) holds, second that maximum rainfall intensity at reference duration, I_{D_0}, follows a GEV distribution. These two assumptions imply that for any duration D, I_D is also GEV-distributed, as will be seen later. The use of a GEV distribution is motivated by extreme value theory (Coles, 2001), which insures that this is the only possible asymptotic distribution of independent and identically distributed maxima. Under this hypothesis, the non-exceedance probability of I_{D_0} is given by:

$$Pr(I_{D_0} \leqslant x) = \begin{cases} \exp\left\{-\left(1+\xi_0 \frac{x-\mu_0}{\sigma_0}\right)^{-1/\xi_0}\right\} & \text{if } \xi_0 \neq 0 \quad \text{(a)} \\ \exp\left\{-\exp\left(-\frac{x-\mu_0}{\sigma_0}\right)\right\} & \text{if } \xi_0 = 0. \quad \text{(b)} \end{cases} \tag{6}$$

Here μ_0, $\sigma_0 > 0$, and ξ_0 are the location, scale, and shape parameters, respectively. Three sub-families of distributions (EV-I, EV-II and EV-III, also known as Gumbel, Fréchet and Reverse Weibull distributions) can be derived from the GEV depending on the sign of its shape parameter, which governs the tail behavior of the distribution. If the shape parameter $\xi_0 > 0$, then the GEV distribution is said to be heavy tailed. This is often the case for rainfall data, in particular in our study area (Ceresetti et al., 2010). The case

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