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Interactive comment on "Evidences of relationships between statistics of rainfall extremes and mean annual precipitation: an application for design-storm estimation in northern central Italy" *by* G. Di Baldassarre et al.

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GENERAL COMMENT

First of all, we would like to thank the Editor, Associate Editor and Reviewers for doing excellent work and providing very useful observations and comments, which truly helped us in improving the overall quality of the presentation of our work. The revised manuscript that we are going to resubmit for possible publication is the proof of our deep appreciation for the useful and constructive indications and suggestions provided by Reviewers. We detail in the remainder of our reply how we incorporated all Reviewers' suggestions and comments in the revised manuscript, which, in our opinion, has

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Interactive Discussion
Discussion Paper

an improved readability and represents an original contribution to the comprehension of the statistical behaviour of rainfall extremes for the study area. A theme of both reviews is the supposed strong similarity between our manuscript and the study by Brath et al. (2003). Prior to the detailed discussion of Reviewers' comments, we would like to remark here the differences and improvements between our study and the analysis described in Brath et al. (2003). By following an approach originally proposed by Alila (2000), Brath et al. (2003) identify a set of generalized depth-duration-frequency equations for the estimation of design storms for storm duration from 1 to 24 hours and test the equations' reliability through a jack-knife cross-validation. We believe that, with respect to previous studies (e.g., Schaefer, 1990; Alila, 1999; Brath et al., 2003), our manuscript presents new data, new concepts and ideas and different tools. For the first time in this study area, our study utilises an updated and significantly enlarged dataset with respect to Brath et al. (2003), which includes sub-hourly rainfall extremes (storm duration of 15 and 30 minutes) and is presented and analysed for the first time (new data). This is acknowledged by one Reviewer (see Bernardara, 2005, p. S1078). We model the relationship between statistical properties of rainfall extremes and mean annual precipitation (MAP) using a Horton-type curve (new concepts and ideas). We show that the curve is statistically significant for all duration considered in the study through an original extensive and objective Monte Carlo simulation experiment that we specifically designed for this purpose, as acknowledged by one Reviewer (see Bernardara, 2005, p. S1079). On the basis of these relationships, we develop a regional model for estimating the rainfall depth for a given storm duration and recurrence interval in any location of the study region (different tool). Perhaps the first version of our manuscript did not present these original contributions clearly enough. Therefore, the changes incorporated in the revised manuscript mainly aim at improving the description of the physical reasoning underlying the development of the analysis, addressing in particular the identification of climatically homogeneous regions. Also, we put more emphasis on the description of the model developed and on the technique used to assess his reliability as suggest by a Reviewer (see Bernardara, 2005, p. S1078). Finally, we included an additional analysis in the revised manuscript (described in a new section 5.3) in order to quantify the sensitivity of regional L-Cv and L-Cs estimates for ungauged sites. In particular, we performed a jack-knife resampling procedure that enabled us to quantify the uncertainty of regional rainfall quantiles for T = 100 and 200 years. These further analyses show that the estimation of the index-storm is the critical step for the application of the proposed regional model to ungauged sites.

The remainder of our reply, after a summary of the revised manuscript structure, addresses the comments raised by Dr. Pietro Bernardara.

REVISED MANUSCRIPT STRUCTURE

We reorganised the revised manuscript as follow:

1 Introduction

2 Index Storm procedure

2.1 Growth factor estimation

2.2 Index storm estimation

3 Study area and locale regime of rainfall extremes

4 Regional model

4.1 Climatically homogeneous pooling-groups

4.2 Empirical regional model for estimating the L-Cv and L-Cs

5 Design storm estimation in ungauged sites

5.1 Application of the regional model

5.2 Index storm and MAP at ungauged sites (section 4.2 in original manuscript)

5.3 Uncertainty of the regional estimates (completely new section)

6 Conclusion

Appendix (Homogeneity test)

REPLY TO REFEREE#1 (Dr. BERNARDARA) The following list describes how the reviewer's suggestions were incorporated in the revised manuscript (the order of the list reflects the order of the comments in the original review).

REFEREE SPECIFIC COMMENT: "Ěa comment on the scaling properties of the estimated index could be very interestingĚ"

We incorporated a comment and a citation in the revised manuscript on scaling properties (Section 4.2): "The overall number of parameters of the regional model might be reduced by looking for scaling relationships in the parameters of the model. With respect to depth-duration-frequency curves, Burlando and Rosso (1996) proposed an approach for limiting the parameterisation requirements by assuming that rainfall depth, once rescaled through a suitable power-law multiplier, follows the same probability distribution for any storm duration. Nevertheless, many authors also showed that it is often violated in practice; rainfall data typically show a transition in their scaling properties for storm duration around 1 hour and shorter (see e.g. Olsson and Burlando, 2002; Marani, 2003). On the basis of these evidences, the scale invariance assumption was not applied in our study."

REFEREE SPECIFIC COMMENT: "Ěcoefficients of variation and skewness are not actually the same that and L-variation and L-skewnessĚ"

We agree with Bernardara and we modified the original manuscript accordingly in two different sections: First change (Section 1): Original manuscript: "For instance, Schaefer (1990) and Alila (1999) showed that the coefficients of variation and skewness of rainfall extremes tend to decrease as the local value of MAP increases. Our analysis has three main goals: (1) investigating the applicability of the studies by Schaefer (1990) and Alila (1999) to the study region; (2) on the basis of the findings obtained at step (1), developing a regional model for estimating design storms for storm duration from 15 minutes to 1 day in any location of the study area and (3) assessing the reliability of the regional model through Monte Carlo experiments." Revised manuscript: "For instance, Schaefer (1990) analysed the rainfall series collected at hundreds of gauges located in Washington State (USA) and showed that the coefficients of variation and skewness of rainfall extremes tend to decrease as the local value of MAP increases. Alila (1999) studied the Canadian raingauge network and detected analogous relationships between the L-coefficients of variation and skewness, L-Cv and L-Cs (for a definition of the coefficients see e.g. Hosking and Wallis, 1997). Brath et al. (2003) identified a similar behaviour of L-Cv and L-Cs of rainfall extremes for the same study area considered herein and storm-duration between 1 and 24 hours. We investigated further the applicability of these outcomes to the study region for sub-hourly storm-duration and, on the basis of the findings obtained, we formalised the relationship between L-statistics of rainfall extremes and MAP through a Horton-type curve (Horton, 1939). Once assessed the applicability of the proposed mathematical expression through an original and objective Monte Carlo simulation experiment, we developed a regional model for estimating design storms for storm duration from 15 minutes to 1 day in any location of the study area and we quantified the uncertainty of the regional model for ungauged sites through an extensive cross-validation." Second change: We incorporated a comment Section 2.1: "The L-moments are analogous to the conventional moments, but they have the theoretical advantages of being able to characterize a wider range of distributions and, when estimated from a sample, of being more robust to the presence of outliers in the data. Hosking and Wallis (e.g., 1997) also point out that L-moments are less subject to bias in estimation than conventional moments."

REFEREE SPECIFIC COMMENT: "Ěthe authors should put the equation of to the L-moments statistics instead the equation of GEV parametersĚ"

The Reviewer is probably suggesting to incorporate the expressions of the sample estimators of L-moments in the text. We do not think that this is a useful add-on to the manuscript as 1) these expressions are reported in the scientific literature (see. e.g., Hosking, 1990; Hosking and Wallis 1997) and 2) we provide a regional model that expresses regional L-Cv and L-Cs as a function of MAP and storm duration. Nevertheless, in order to clarify this point, we included a comment at the end of section 2.1. Original manuscript: “where L-CvR and L-CsR are, respectively, the 2nd and 3rd order standardised regional L-moments.” Revised manuscript: “where L-CvR and L-CsR are, respectively, the 2nd and 3rd order standardised regional L-moments. Hosking and Wallis (1997) illustrate in detail the general procedure for computing L-CvR and L-CsR for a particular pooling-group of sites (i.e., a geographical region or a set of raingauges). Our study develops a regional model for estimating L-CvR and L-CsR for the storm duration of interest from the local MAP value (see section 4).”

REFEREE SPECIFIC COMMENT: “Ěthe hypothesis that lead to the derivation of the GEV following the extreme value theoryĚ”

The original manuscript (Section 2.1) was changed as suggested: Original manuscript: “Several recent regional analyses showed that the Generalised Extreme Value (GEV) distribution (Jenkinson, 1955) is a suitable statistical model for representing the frequency distribution of rainfall extremes over the study area (see e.g., Franchini and Galeati 1994; Brath et al. 1998).” Revised manuscript: “The Generalised Extreme Value (GEV) distribution (Jenkinson, 1955) subsumes all three different extreme-value distributions (i.e., EV type I, II and III), to which the largest/smallest value from a set of independent and identically distributed random variables asymptotically tends. Consistently, several recent regional analyses showed that the GEV distribution is a suitable statistical model for representing the frequency regime of rainfall extremes over the whole study area (see e.g., Franchini and Galeati 1994; Brath et al. 1998).”

REFEREE SPECIFIC COMMENT: “Ěthe confidence of L-moments calculated on N$>$5 series is different from the confidence of L-moments calculated on a N=30 seriesĚ”

The revised manuscript comments (Section 3) on the criteria reported in Table 1 and their possible effects on the reliability of sample L-moments: “As Table 1 shows, we considered all available series of sub-hourly rainfall with at least 5 years of measure (N ≥ 5). This criterion reflects our intention of incorporating into the analysis as much information as possible. The raingauge network for sub-hourly storm duration is more recent and sparser than the network for hourly and daily storm duration (see Table 1). In order to reduce the negative effects of sampling variability for short series we characterised the statistics of rainfall extremes locally at each site through sample L-moments estimators, as they tend to be less biased than sample estimators of traditional statistical moments for orders 2 and higher and small samples (e.g., Hosking, 1990; Hosking and Wallis, 1997). For the same reason, as suggested for instance in Hosking and Wallis (1997), we characterised the frequency regime of rainfall extremes at a regional scale (i.e., for a group of raingauges) by weighting each sample L-moment proportionally to the sample length.”

REFEREE SPECIFIC COMMENT: “ĚH(1) on groups of 15-30 stations and H(2) on groups of 30-60 stationsĚ”

In the revised manuscript we commented about our choice (Section 4.1): “The different numbers of raingauges considered for the homogeneity testing (i.e., 15 and 30 for H(1) and 30 and 60 for H(2)) reflect two different aspects. First, higher order L-moments tend to be more homogeneous in space than the lower order ones (see e.g., Hosking and Wallis, 1997), therefore pooling-groups of sites for which the homogeneity is assessed in terms of L-Cv and L-Cs (i.e., use of H(2)) may be lager than pooling-groups for which the homogeneity is assessed in terms of L-Cv only (i.e., use of H(1)). Second, heterogeneity measures such as H(1) and H(2) are better at indicating heterogeneity in large regions, while have a tendency to give false indications of homogeneity for small regions, therefore pooling groups should be as large as possible.”

REFEREE SPECIFIC COMMENT: “The uncertainty related to the L-moments estimation are more or less important that the uncertainties of each components of the rainfall

HESSD

2, S1525–S1536, 2005

measures (mean annul maxima and the extremes)?"

We addressed this comment by including additional analyses in the revised manuscript in a totally new section 5.3. We used a jack-knife resampling procedure to quantify the sensitivity of regional L-Cv and L-Cs estimates for ungauged sites. In particular, this study enabled us to quantify the uncertainty of the regional rainfall quantiles for T = 100 and 200 years and to compare it to the uncertainty associated to the index-storm estimates. The results of these further analyses show that the estimation of the index-storm is the critical step for the application of the proposed regional model to ungauged sites. The revised manuscript included a new section 5.3 that describe this analysis: "We evaluated the performance of the regional model through a comprehensive a jack-knife cross-validation (see e.g., Brath et al., 2001). The cross-validation procedure enabled us to compare the regional and resampled estimates of the design storm at all considered raingauges for two arbitrarily selected duration: 1 and 24 h and two reference recurrence intervals: 100 and 200 yrs, which are normally adopted in Italy for designing flood risk mitigation measures. Through this comparison we quantified the uncertainty of the design storm estimates that can be computed by applying the proposed regional model to any ungauged site within the study area. In particular, we compared the regional estimate of the dimensionless growth factor, h'(d,T), and design storm, h(d,T), with their resampled counterparts, h'jk(d,T) and hjk(d,T), respectively. We computed h'jk(d,T) and hjk(d,T) as follows: 1) one of the NS raingauges, say station i, and its corresponding data are removed from the set; 2) the parameter a, b and c of model (6) are estimated on the basis of the pluviometric information collected at the remaining NS-1 raingauges; 3) jack-knifed regional L-moments, L-CvRjk and L-CsRjk, are calculated for site i by using the recalibrated model (7) identified at step 2) and the jack-knifed MAP value (MAPjk) retrieved for site i from isoline MAP generated through ordinary kriging as described in section 5.2; 4) the jack-knifed parameters of the regional GEV distribution are estimated for site i through the method of L-moments on the basis of the L-CvRjk and L-CsRjk values estimated at step 3); 5) h'jk(d,T) is computed for site i as the T-year quantile from the GEV distribution estimated at step

4); 6) hjk(d,T) is then computed as the product of h'jk(d,T) and the jack-knife estimate of md, which is calculated as described in section 5.2; 7) steps 1-6 are repeated NS-1 times, considering in turn one of the remaining raingauges. The box-plot diagram of Figure 11 shows the distributions of relative errors for the estimation of the growth factor h'(1 h,100 yrs) and h'(24 h,100 yrs) and the design storm h(1 h,100 yrs) and h(24 h,100 yrs). Figure 12 shows the distributions of relative errors for the estimation of the growth factor h'(1 h,200 yrs) and h'(24 h,200 yrs) and the design storm h(1 h,200 yrs) and h(24 h,200 yrs). The figures show that the application of the proposed regional model to ungauged sites provides unbiased estimates of h'(d,T), for d=1, 24 h and T=100, 200 yrs. Also, Figures 11 and 12 illustrate that the absolute value of relative errors of the dimensionless regional growth factors is generally small and always lower than 10%. It is important to notice that if the local value of MAP is know (e.g., from observed daily rainfall data), then the relative errors of h'(d,T) estimates, resulting from the uncertainties in the parameters of model (6), become practically negligible ($<$1%). Concerning the estimation of h(d,T) the performance of the model is definitely lower as 30%. A comparison between the relative errors of Figure 11 and 12 points out rather clearly that the largest uncertainty in the application of the regional model to an ungauged site is associated with the index-storm estimates (see section 5.2)."

REFEREE TECNICHAL CORRECTION: Line 23, p2399. We agree with the Reviewer, in the revised manuscript we defined L-kurtosis as L-Ck in order to maintain the coherence between the formal representations of L-moments.

REFEREE TECNICHAL CORRECTION: Caption of figure 4. We removed Figure 4 from the manuscript.

REFEREE TECNICHAL CORRECTION: Line 6, p2404. The suggested change was incorporated in the revised manuscript.

REFEREE TECNICHAL CORRECTION: Figure 4, Figure 5a and Figure 5b. We agree with the Reviewer that one should not present the same material twice. Therefore we

HESSD

2, S1525–S1536, 2005

Interactive Comment

removed Figure 4 from the manuscript.

REFEREE TECNICHAL CORRECTION: Line 14, p2404. The Reviewer is right, we modified the conflicting sentence as follows. Original manuscript: “The cross-validation produced the best performance indexes combining a linear regressive model, for representing the relationship elevation-MAP, with a KLV spatial interpolation of relative residuals” Revised manuscript: “We tested several possible options as for regression models and variograms, and we obtained the best performance indexes after cross-validation for this particular case (i.e., ordinary kriging of relative residuals) by combining a linear regressive model for representing the relationship elevation-MAP, with a KLV spatial interpolation of relative residuals.”

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