Precipitation paper, Anonymous Referee #1

GENERAL COMMENTS AND RECOMMENDATION

The manuscript presents an exercise of geo-statistical simulation of rainfall fields conditioned to rain gauge measurements. The experiment is based on generating ensembles of rainfall fields using the well-known sequential simulation approach (Goovaerts 1997). The exercise assumes spherical variograms to model the spatial and temporal variability of the rainfall field. The generator has been applied for some synthetic and real situations in the Belgian Ardennes. The manuscript is well written and technically correct. Also, the potential applications of the developed ensemble generator are multiple (although they could be further discussed), which makes the presented development very interesting. However, the presented study is limited to demonstrate the sequential simulation algorithm and to analyze the dependence of the Coefficient of Variation on different factors (such as the time-memory of the ensemble, size of the catchment, speed of the system). However, the interest of some of the analyses is not very clear or not discussed enough, and little interpretation of the presented results is provided. Therefore, I cannot recommend the publication of the manuscript in its present form. I encourage the authors to make major modifications to the manuscript, and in particular to illustrate the potential of the algorithm with some further application of the generated ensembles.

Answer:

We thank Anonymous Referee #1 very much for her/his constructive review. We will explicitly justify the interest of the presented analyses in the introduction and add a reference to the actual hydrological application of the presented spatial precipitation ensemble generator (see further our answer to major comment #1) .

MAJOR COMMENTS

1) The Introduction mentions that the objective of the study is to “define a plausible precipitation ensemble generator using rain gauges”. However, further justification of the interest of the developed methodology could be useful for the reader.

Answer: The justification of the interest of the developed methodology is provided in the Summary and Conclusions on Page 3104, last paragraph. However, we will justify our interest more clearly in the abstract and will add an extra paragraph in the introduction. Additionally, we will add a reference to Rakovec et al. (2012), the actual hydrological application of the presented spatial precipitation ensemble generator, which is currently under review for HESS in this special issue on "Latest advances and developments in data assimilation for operational hydrologic forecasting and water resources management".

2) What are the parameters needed in the ensemble? I miss some further analysis/discussion on how the different parameters could be estimated in a real situation.

Answer: The parameters needed for the ensemble simulation are those of the fitted spherical semi-variogram model described on Page 3092, lines 3-9, i.e., nugget, partial sill and range. The time lag is not considered explicitly as a parameter of the space-time dependency. We applied the spherical variogram model, because all three parameters have a physical meaning and are often used to obtain spatial precipitation estimates (Page 3092, lines 3-4). We will make a clear link between Sect. 2.2 and Sect. 2.3 and we will add a clear description on how those model parameters were obtained/fitted. This corresponds also to the comments raised by Anonymous Referee #2 and Martinus van den Berg (Referee #3).

The gstat R package function fit.lmc() was employed to fit the variogram models using the weighted least square fit as a goodness-of-fit. The default method uses weights N_h/h^2, where N_h the number of point pairs and h the distance (Pebesma, 2004). The initial model parameters of the spherical variogram model were set as follows: partial sill = 0.1mm, range =

70000m and nugget=0.02mm. Function fit.lmc() ensures as well that the system is positive definite (Pebesma, 2004).

3) Some discussion on the implications of the used semi-variogram is needed. a) How would the results depend on the semi-variogram model? b) Would it be feasible to use sample semi-variograms? c) Is the spatial anisotropy of the rainfall field considered?

Answer: The reviewer indeed raises an interesting point. However, our main interest was to identify the impact of adding temporal information on the uncertainty in simulated precipitation fields. Therefore we decided to keep the parametrization as simple as possible (simple variogram model with no anisotropy). This simple variogram has been shown in other papers to be well able to represent the spatial variability of the precipitation field as measured by rain gauges. Therefore, we will provide some discussion in the new version of our manuscript as follows:

a) The spherical variogram model is a very widely employed variogram model for rainfall (e.g. Berne et al., 2004; Schuurmans, et al., 2007; van de Beek et al., 2011; Verworn and Haberlandt, 2011). Certainly, the choice of variogram model involves some subjectivity. The results are not expected to change radically if another variogram model would have been chosen.
b) No, because they generally do not satisfy the requirements for simulation (Goovaerts, 1997).
c) The spatial anisotropy was not considered in the variogram model. Although this is certainly a relevant issue, it is beyond the scope of the current study.

MINOR COMMENTS

1) Page 30, line 4: “precipitation estimates by weather radar are prone to biases”. Not only to biases but, in general, prone to errors. Similarly, page 30, line 7: rain gauge measurements are not only “to adjust radar precipitation fields for bias”, but to mitigate the errors in radar rainfall estimates.

Answer: We will change word “biases” to “errors” on Page 3089, line 4. Additionally we will change the sentence on Page 3089, line 7 “... adjust radar precipitation fields for bias” to “... mitigate the errors in radar rainfall estimates”

2) Page 3092, line 18. Do the authors mean Eq. (1)?

Answer: Yes, that is a mistake and we meant Eq. (1). We will correct it in the revised manuscript.

3) In Eq. (3) it could be mentioned that i,j stand for the time steps.

Answer: This is a good idea. We will mention this in the revised manuscript, however, we will change those indices i,j to p,q, such that they won't be confused with sub-indices j,t (see next comment).

4) The notation of Eq. (4) is not very intuitive. I was confused by sub-indices j,t.

Answer: We would prefer keeping those j,t sub-indices, because in the data assimilation literature j is often an index for an ensemble member, J for ensemble size and t for time step. However, we will change indices in Eq. (3) from i,j to p,q (see previous comment).

5) Page 3095, lines 5-9: “This approach is widely employed by catchment hydrologists, who are interested in the overall uncertainty over the precipitation event (. . .). The second way quantifies the uncertainty across the ensemble for each individual time step and is more of an interest for hydrologists dealing with flood forecasting”. Could the authors develop this argument a little bit more?

Answer: We agree that the distinction is not very clear. We mean that the across-ensemble uncertainty at a given time step is highly relevant for hydrologists employing Kalman filtering approaches in flood forecasting (e.g. Weerts and El Serafy, 2006), whereas the variability of a single realization over time during an event, giving rise to uncertainty in the accumulated rainfall, is a typical source of uncertainty dealt with by hydrometeorologists (e.g. Mandapaka et al., 2010, Kirstetter et al., 2010), catchment hydrologists (and rainfall-runoff) modellers (e.g. Brauer et al., 2011).

6) Page 3096, line 8, and elsewhere: “a synthetic spherical rainfall cell”. Would it be a circular rainfall cell?

Answer: We thank the reviewer for this remark. Proper description seems to be “a circular-shaped rainfall cell” (because of 2D), which was suggested by Martinus van den Berg, Referee #3. We will change this in the revised manuscript.

7) Kriging is known to produce Best Linear Unibiased Estimates. However, the simulation is done over the transformed variable. How does it affect the simulations of rainfall? Would they be biased? How would this affect the use of these ensembles?

Answer: Because of the skewness of the pdf of rainfall accumulations, particularly at shorter time scales, applying kriging/simulation to untransformed rainfall amounts will introduce a bias (e.g. Schuurmans, et al., 2007). Although we agree that this is an important aspect, we considered it beyond the scope of the current study.

8) Figs. 10-12. I would recommend the authors to explicitly mention in the figure captions that the different points in each panel are for different points of the basin. In the caption of Fig. 11 “for four ensemble realizations”: are not the panels for four time steps?

Answer: Yes, we will mention that the different points in each panel are for individual points (pixels) of the sub-catchments. You are right, correct phrasing is “for four time steps” instead of “for four ensemble realizations”. We will correct this in the revised manuscript.

9) Page 3101, first paragraph: I miss some further interpretation of these results. The differences in the different panels of Figs. 13 and 14 are only due to the sampling sizes? How are the results in the smaller catchments location-dependent? Would they significantly change in other subdomains of the same size?

Answer: This is indeed an interesting observation. To analyse this comment we show in the following figures (Fig. I) the coefficients of variation for five different subdomains of the same catchment sizes as in Figs.13 and 14. Apparently, the differences in the panels are location-dependent, especially for smaller catchments where the largest uncertainty was obtained. This sampling error is caused by the fact that only limited a number of points is used to calculate the coefficient of variation. Additionally, we can observe that this uncertainty is decreasing for larger catchments. However, when we calculated the mean coefficient of variation for each catchment size and advection speed, we observe hardly any difference between the mean values of coefficients of variations for different catchment sizes.

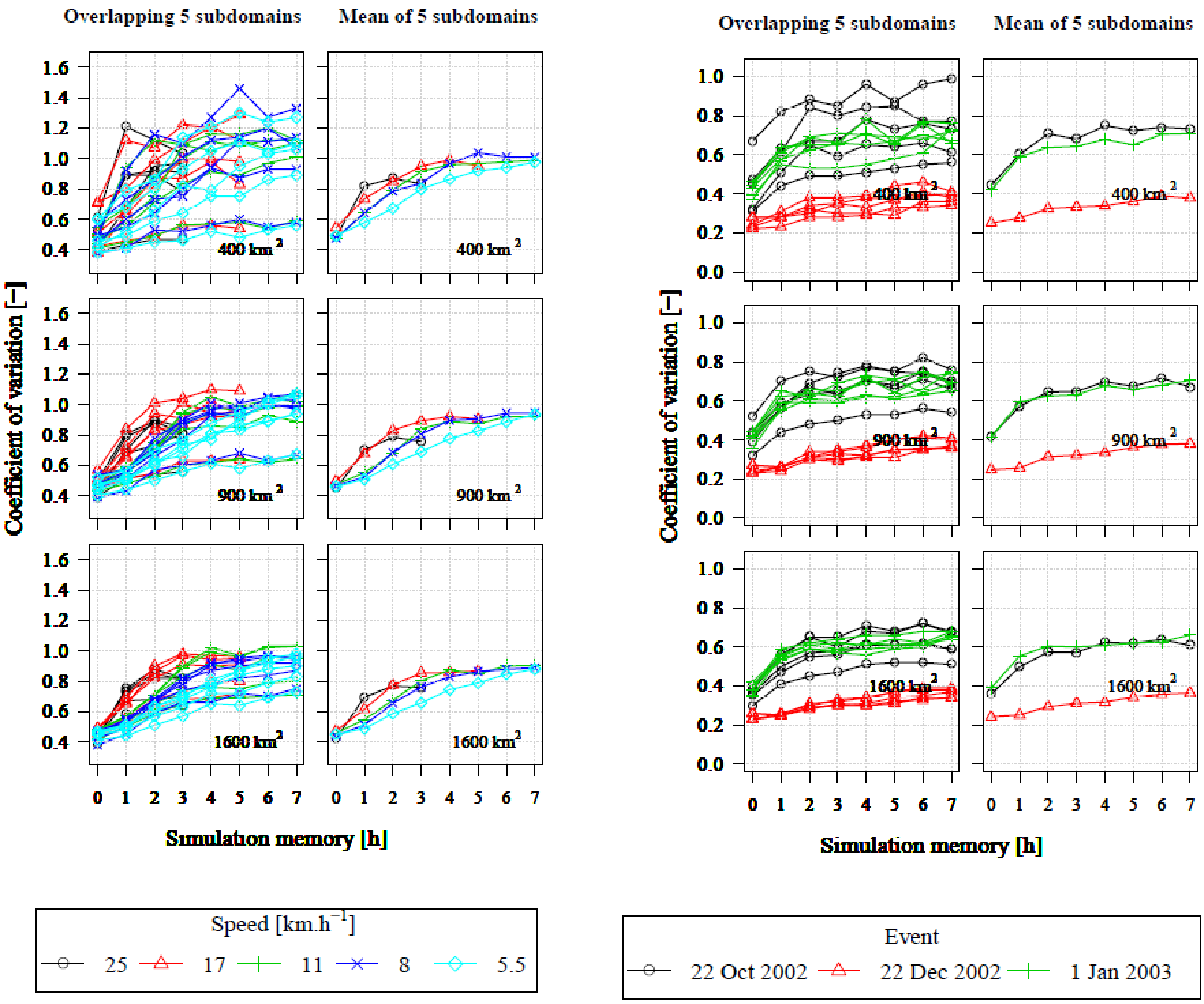

Figure I: Coefficient of variation (CVJ) for different catchment sizes and advection speeds and five different subdomains. Synthetic sensitivity experiment (left) and real world experiment (right). See answer to comment #9 for detailed description.

10) Page 3102, lines 6-10: "Nevertheless, the impact of this discontinuity decreases for larger catchments, which is caused by a limited spatial extent of the synthetic spherical rainfall cell advecting over the catchment". It is unclear what the authors mean.

Answer: We hope that following sentence will be more clear: "Nevertheless, the big difference between the univariate simulations (simulation memory 0h, grey boxplots in Fig. 15) and the multivariate simulations (simulation memory 1-7h, white boxplots in Fig.15) decreases for larger catchments. This is a direct result of the relatively small size of the rain cell with respect to the catchment area."

11) a) Page 3102, lines 9-11: Please, add a comma after ". . .using the lumped CVJ". b) Lines 11-13: specify "By fitting the spherical model, the range of the variogram can be obtained".

Answer: a) Yes, we will add a comma after CVJ. b) We will explain how the range of the spherical model was obtained. This will be an analogy to the planned explanation of the major comment #2.

12) Fig. 16. How was the advection speed of the real-world cases estimated?

Answer: The advection speed for the three precipitation events was obtained by estimating the mean speed of the precipitation system during the event. We identified the precipitation system based on observed volumetric radar data for which the reflectivity had to exceed 7 dBZ (~1 mm/h).

13) Equation (10). Please, specify that the range in the equation has units of time.

Answer: Yes, we will specify that range has units of time [h].

14) The authors model the time correlation of the rainfall field in fix coordinates (from the rain-gauge perspective), and equation (10) and Fig. 16 show that the slower the systems, the larger the time correlation. However, rainfall fields show significantly larger time correlation in moving coordinates (i.e. removing the effect of advection in the evolution of the rainfall field), which is independent of the advection speed. For instance, the time correlation of the synthetic experiment in moving coordinates would be exactly 1. In this sense, realistic rainfall ensembles should also reproduce the time correlation of rainfall systems in moving coordinates. Could the authors comment on this aspect?

Answer: The reviewer is right. We assume that realistic realizations reproduce the temporal correlation in Eulerian coordinates, on which we focus in the current paper. From a catchment hydrological perspective using Eulerian also is more natural given the fact that the region of focus is rather large. In case it is assumed that our gauge network is dense enough to grasp most spatial variability, for a considerable number of time steps using a Lagrangian coordinate system would not lead to different results. This of course is in case the density of the gauge network decreases or the precipitation region moves beyond our region of focus.

15) It could be interesting to know the authors' opinion on how could radar data be used to further condition the generated ensembles.

Answer: Obtaining precipitation ensembles from radar remains an important continuation of this study indeed. The main benefit of using radar is that one obtains much more information on the spatial characteristics of both the precipitation field and type (Hazenberg et al., 2011). It is then possible to take two different approaches. 1) the rain gauge perspective, where we imagine that that the weather radar data is only used to provide information on where it rains and which gauges are specifically used to generate a variogram (since they belong to the same region). 2) The radar perspective, where the gauges are used to correct the radar for any remaining bias, while the uncertainty in the precipitation field is obtained from the volumetric radar information. We will present some ideas on these issues and approaches related to these issues in upcoming publications.

16) Some of the figure panels (e.g. Figs. 5-9, 13-15) are too small.

Answer: The small panels of those figures are caused by a rather limited width of the HESSD layout. The final HESS layout has a bit more space for figures, which means the panels will be larger. However we will make sure that the figure panels are easily readable in the final version of the manuscript.

List of references:

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