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Exploring the signature of climate and landscape spatial variabilities in flash flood events: Case of the 8–9 September 2002 Cévennes-Vivarais catastrophic event

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[1] This paper investigates the signature of climate and landscape spatial variabilities on flash-floods events. Through the case of the catastrophic 8–9 September 2002 Cévennes-Vivarais event, the impact of the space-time structure of the rainfall on the distributed hydrological response is evaluated. Comparisons are made with other spatial variabilities that may also contribute to the flash-flood generation such as initial soil moisture condition, topography, landscape characteristics, hydraulic processes. A model-based approach is suggested and was applied on 19 catchments. It is shown that the spatial variability of rainfall and of the initial soil moisture conditions were both of first order in the flash-floods generation and that the spatial variability of landscape properties were of second order. This methodology will be applied on other extreme hydro-meteorological events surveyed by the OHM-CV (Cévennes-Vivarais Mediterranean Hydrometeorological Observatory), with the aim of providing clues on processes that should be particularly focused when measuring and simulating such intense mesoscale meteorological events. **Citation:** Le Lay, M., and G. M. Saulnier (2007), Exploring the signature of climate and landscape spatial variabilities in flash flood events: Case of the 8–9 September 2002 Cévennes-Vivarais catastrophic event, *Geophys. Res. Lett.*, *34*, L13401, doi:10.1029/2007GL029746.

1. Introduction

[2] An accepted result is that the accurate estimation of the areal rainfall is first needed when studying flash-flood generation. Nevertheless, deeper investigations or better localized flood forecast need an improved knowledge of the climate and landscape interactions that control distributed hydrological response. But these goals face strong difficulties due to the highly non-linear hydrological processes leading to threshold effects and spatio-temporal variabilities of their combinations during an event.

[3] The recent development of distributed models allows to investigate the role of spatial variabilities of landscape characteristics and of meteorological forcing on the hydrological response-see for instance the recent DIMP (Distributed Model Intercomparison Project) initiative [*Smith et al.*, 2004]. Existing studies focus on: (i) the role of rainfall spatial variability [*Obled et al.*, 1994; *Winchell et al.*, 1998; *Koren et al.*, 1999; *Arnaud et al.*, 2002]; (ii) the role of initial soil moisture conditions [*Zehe et al.*, 2005]; (iii) the role of catchment characteristics [*Saulnier et al.*, 1997]; (iv) the competition between the different variabilities [*Boyle et al.*, 2001; *Andréassian et al.*, 2004]. All these studies outline the influence of threshold effects in runoff generation, hence suggesting the difficulty to extrapolate results to other catchments.

[4] This paper aims at going one step further into this issue by evaluating the ranking of the significance of the spatial variabilities that influenced the 8–9 September 2002 severe event, only at the meso-scale (4500 km^2) and for 19 catchments ranging from 50 km^2 to 2240 km^2. This work is inspired by the downward approach [*Klemes*, 1983; *Sivapalan et al.*, 2003], which has shown an appropriate way to gain insight into the climate and landscape factors controlling hydrology [*Jothityangkoon et al.*, 2001; *Farmer et al.*, 2003]. However, in what follows, different simulations are performed with the same hydrological model, i.e. with the same model structure complexity. For each simulation, different spatial variabilities will be successively added and discharges estimations will be compared to the observed discharges time-series of the 19 catchments. The gains thus obtained by taking into account such and such spatial variabilities will then be compared, which will allow the ranking of the comparative significance of the latter.

2. Case Study of the 8–9 September 2002

[5] The 8–9 September 2002 heavy precipitation event was responsible for one of the most important floods ever recorded in the Cévennes-Vivarais region. It caused 24 casualties and economic damage estimated to 1.2 billion euros. A detailed meteorological description of this event is provided by *Delrieu et al.* [2005]. Therefore, only a brief overview will be given here.

2.1. Geographical Region

[6] The Cévennes-Vivarais region is located southeast of the Massif Central, the V-shaped Hercynian mountain range of the central part of France (Figure 1). The altitude of the mountain range varies from sea level to up to 1700 m over roughly 70 km. Like other Western Mediterranean regions and particulary in autumn, Southeastern France experiences long-lasting rain events able to produce catastrophic floods over a wide range of river basin sizes (from 100 up to 10 000 km^2).

[7] The hydrological survey of the Cévennes-Vivarais observatory covers the three main catchments studied in this paper which are the Gardons catchment at Ners station (1090 km^2), the Cèze catchment at Bagnols-sur-Cèze station (1110 km^2) and the Ardèche catchment at Sauze-Saint-

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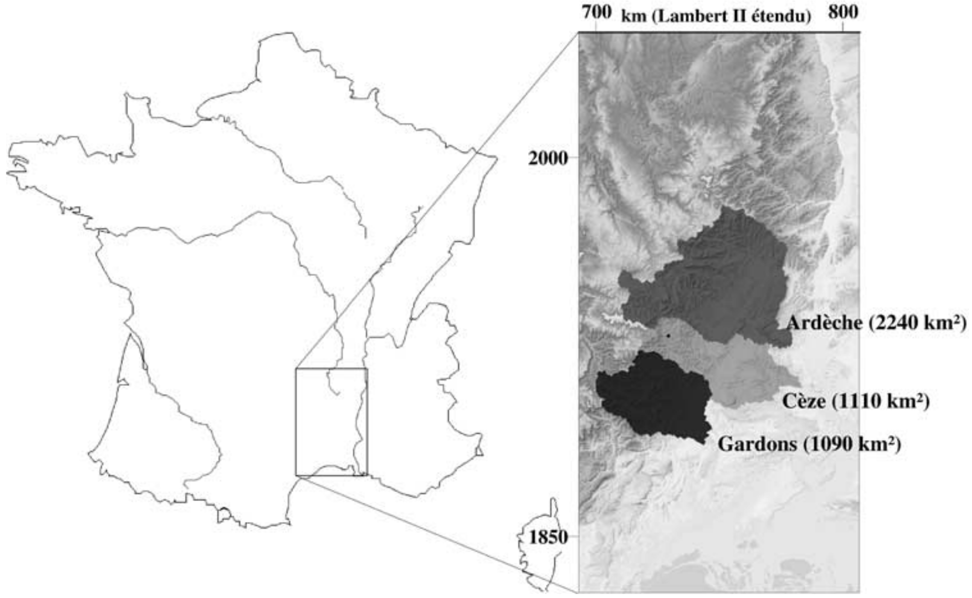

Figure 1. Location of the Cévennes-Vivarais window in France and of the three basins covered by the study.

Martin station (2240 km^2). In what follows, these three catchments will be referred to as 'the river basins'.

2.2. Hydrometeorological Description

[8] In the Cévennes-Vivarais region, heavy precipitation are usually due to quasi-stationary mesoscale convective systems (MCS) whose lifespan of several hours leads to high cumulative rainfall amounts. For example, in the case of the 8–9 September 2002, the rain event lasted approximately 28 hours. It was particularly remarkable by its spatial extension, with rain amounts greater than 200 mm over 5500 km^2 in 24 hours. Heavy amounts primarily affected the Gardons river, with about 500 mm recorded in less than 9 hours at Anduze rain gauge. Finally, the areal 24h-cumulated rainfall reached 300 mm for the Gardons river basin, 200 mm for the Cèze river basin and about 100 mm over the Ardèche river basin.

[9] Indeed, the hydrological impacts were dramatic. In some catchments, the specific discharge raises to values up to 3–4 m^3 s^{-1} km^{-2} on catchments of several 100 km^2 and up to 7 m^3 s^{-1} km^{-2} on catchments of several 10 km^2 [*Delrieu et al.*, 2005].

3. Material and Method

3.1. Available Data

[10] The 160 km × 200 km Cévennes-Vivarais window synoptic hydrometeorological measurements network include 400 daily and 180 hourly rain gauges and 45 water level stations. For this particularly extreme storm event, some of these river gauges were destroyed or out of order. Finally, 19 water level stations were chosen for this study, spread as follows: 7 gauges for the Ardèche river basin, 6 gauges for the Gardons river basin and 6 stations for the Cèze river basin. The hourly rainfall fields were obtained by krigging the hourly rain gauges with special emphasis as detailed below.

3.2. Hydrological Simulation

3.2.1. Spatial Resolution

[11] The spatial resolution was determined considering the spatial variability structure of the rainfall, as studied by *Lebel et al.* [1987]. Following *Berne et al.* [2004], a maximal spatial resolution may be deduced from the variogram. For the hourly rain gauges available for this study it leads to suggest that a maximal resolution of 70 km^2 should be enough to ensure an accurate spatial variability representation of the krigged rainfall fields. Therefore, a 50 km^2 spatial resolution of the krigged hourly rainfall fields was then chosen for this study.

[12] The three river basins were then divided in 90 subcatchments of similar area equal to $\simeq$50 km^2, using classical topographic treatment routines derived on the detailed 50 m DTM available for this study. Each of these subcatchments is called 'hydrological mesh' in what follows.

3.2.2. Processes Representation

[13] Previous studies showed that the hydrological response of Cévennes-Vivarais catchments is mainly controlled by subsurface flows and quick runoff generation on variable contributing areas [*Cosandey and Didon-Lescot*, 1990; *Lardet and Obled*, 1994; *Taha et al.*, 1997]. Then, the well known TOPMODEL framework [*Beven and Kirkby*, 1979; *Beven et al.*, 1995] was used in this study. Indeed, it was one of the first attempts to model distributed hydrological response based on these processes. Previous studies showed that TOPMODEL is well suited to describe this kind of catchments [*Obled et al.*, 1994; *Saulnier et al.*, 1997; *Saulnier and Datin*, 2004].

[14] Basically, given some assumptions and approximations, TOPMODEL predicts the spatial distribution of the soil water content at each time step. That is a function of the spatial variability of an index of hydrological similarity and of the mean overall water storage (or storage deficit), based on the water balance estimated at each time step. The

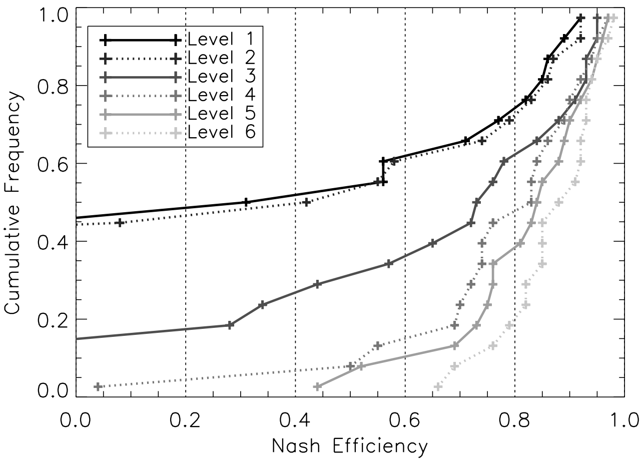

Figure 2. Cumulative distributions of regional model performances, for the 6 levels of spatial information.

topographic variability within a particular catchment is then synthesized by a statistical empirical distribution function of this index of hydrological similarity.

[15] Deeper details are given by *Beven et al.* [1995], *Saulnier et al.* [1997], or *Saulnier and Datin* [2004]. The version used in this paper is an event-based version, with four parameters: (i) an hydrodynamic soil characteristics set including the hydraulic soil conductivity at the surface (K_0 (m s^{-1})) and its exponential decrease with soil depth (*m* (m)), (ii) the initial water content of the superficial soil layer at the beginning of the storm event (*SRMax* (m)), and (iii) the evapotranspiration losses rate (*Inter* (m s^{-1})).

[16] The TOPMODEL framework is then applied on each hydrological mesh, at an hourly time step, to estimate the two discharges components: the soil subsurface exfiltration flows and the quick soil surface runoff.

3.2.3. Transfer Algorithm

[17] In order to estimate the summed discharge at any point of the river network of the 4500 km^2 studied region, a geomorphological approach was used to sum the calculated water fluxes for each hydrological mesh. Firstly, for each DTM pixel, distance to the closest river network is derived. Secondly, distance between any points in the river networks is also derived. Simple assumption on river propagation velocity and runoff on hillslope velocity are enough to calculate time delay between any DTM pixel and any river pixel [see *Zin and Obled*, 2007].

3.2.4. Model Implementation

[18] The results presented hereafter are based on the following step by step model implementation.

[19] A first 'lowest information level' is defined. In this step, topography, areal rainfall, soils hydrodynamics characteristics, velocities transfer parameters and initial soil water content are set to be equal on each hydrological mesh. To do this the overall hydrological index distribution function of the three river basins are forced for each hydrological mesh, rubbing out any local topographic variability. The areal rainfall of the three river basins are applied on each of their hydrological mesh. The same is done for the initial soil water content. Finally the same model parameters (hydrological parameters and velocities parameters) are set to be equal for each of the hydrological meshes within a river basin. This first level is referred to as level 1 in what follows.

[20] Then, different levels have been defined by adding successively more and more spatially distributed data as follows.

[21] 1. For level 2 the specific similarity index distribution function of each hydrological mesh is used here rather than the global one as in level 1. This amounts to inputting the space structure of the topography.

[22] 2. For level 3 the areal rainfall of each hydrological mesh is also used here.

[23] 3. For level 4 the initial water content of each hydrological mesh is also used here.

[24] 4. For level 5 varying hydrological parameters are allowed to be different for each hydrological mesh.

[25] 5. For level 6 varying velocities transfer parameters are allowed to be different for each hydrological mesh. Level 6 corresponds to the 'highest information level' as it takes into account the maximal amount of spatial variabilities that can be input in the model.

[26] For each of these information levels, the hydrological model is calibrated on the three river basins outlets using a Monte Carlo uniform sampling as calibration procedure and the Nash efficiency [*Nash and Sutcliffe*, 1970] as objective function. The Nash efficiencies are then calculated for the 16 other gauged river outlets which are never used for the calibration (except for level 6) and should then be considered as 'blind test' gauged river stations. The empirical cumulative distribution function of the 19 Nash efficiency values are then calculated for each of the 6 different information levels. Results are shown and discussed in the following section.

4. Results and Discussion

[27] Figure 2 shows the empirical cumulative Nash efficiencies for the 19 gauged river station and for the 6 information levels. The more the distribution is shifted to the right, the better the model simulation is.

[28] Level 1 distribution corresponds to the lowest model likelihood using none of the spatial variabilities. Level 6 distribution corresponds to the highest model likelihood for this storm event in this region using as much data as possible. In between, the other distributions and their relative shift from the previous level to level 6 illustrate the relative impact of taking into account such and such spatial variability. It is then possible to evaluate the relative contribution of each spatial variability to the flood generation.

[29] Results on Figure 2 then suggest the following.

[30] 1. The 1 and 2 information levels do not lead to relevant simulations of the flood. In particular, the use of the spatial variability of the topography characteristics does not improve model performance. This does not mean that the topography does not have any influence on the runoff generation, but that the topogography is relatively homogeneous within these catchments. This can be confirmed by the relative homogeneity of the topographic features observed in the Cévennes-Vivarais basins.

[31] 2. Taking into account the spatial variability of the rainfall (level 3) greatly improves the model simulations.

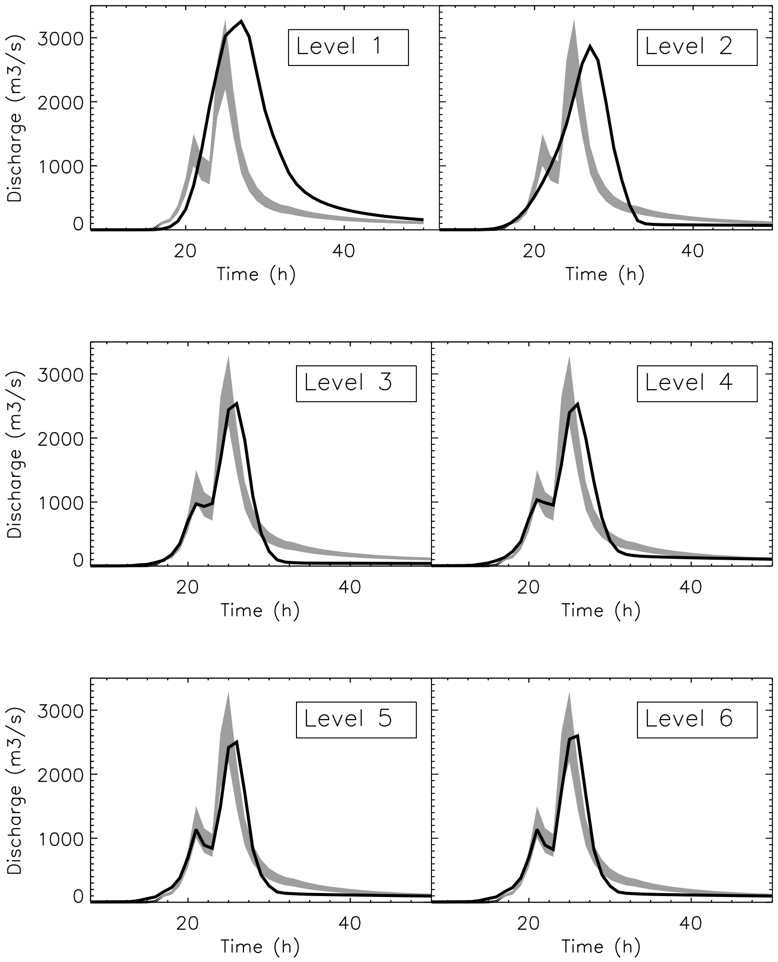

Figure 3. Discharge simulations at the Anduze station (Gardons river, 545 km^2), for the 6 levels of spatial information. Observed discharges are figured in grey (with indicative 20% uncertainty intervals). Simulated discharges are figured in black.

Therefore, this spatial variability has a major signature on the regional hydrological response.

[32] 3. Spatialized initial soil water content (level 4) also significantly improves flash flood representation.

[33] 4. Spatial variability of transfer velocities (level 5) has a second order effect on flash flood representation, but is not negligible.

[34] 5. Spatial variability of landscape characteristics (level 6) has also a second order impact on model simulations.

[35] Figure 3 focuses on the Gardons river basin at the Anduze gauged station (545 km^2) where the maximum areal rainfall was observed. Discharges simulations of each information level are displayed on the figure. This figure suggests that the main breakthrough occurs at level 3. When taking into account the spatial variability of the rainfall both peak flow and its timing are better estimated. Furthermore it is worth noting that the bi-modal feature of the flood is now reproduced. Additional variabilities (level 4 to level 6) still improve the simulations but give only few greater insights on the flood dynamic.

5. Conclusions

[36] The step by step hydrological model implementation proposed in this paper suggests that the catastrophic 8–9 September 2002 Cévennes-Vivarais flash flood event was mainly controlled by the space-time structure of the rainfall and of the initial soil water content. The space structure of the soils hydrodynamic characteristics and of the transfer velocity within the river network were of second order.

[37] This in turn suggests that the emergence of coupling between hydrological models and SVAT models (Soil Vegetation Atmosphere Transfer models) should be carried on since the initial soil water content prior to this kind of dramatic rainfall event may be of first order as shown in this paper. This is contradictory to an accepted result that when the rainfall amount is very high, the flood is less sensitive to the initial soil water content. Furthermore, the fact that the space structure of the initial soil water content prior to the storm event is of first order in the flood generation suggests that initializing such a distributed regional hydrological model with soil water contents simulated by SVAT models during the inter-storm may be a valuable validation test for such models.

[38] Finally, results discussed in this paper also suggest the important need for the use of meso-scale meteorological model in flash-flood warning procedure. Indeed, the spatial structure of the rainfall appeared to be the main factor controlling this flash event. Moreover, the use of meso-scale meteorological models seems to be a promising

solution to provide accurate forecasts of the spatial structure of the rainfall at lead-time of several hours (i.e. the time-response of these catchments).

[39] Within the Cévennes-Vivarais Mediterranean Hydrometeorological Observatory [*Delrieu et al.*, 2005], the application of this approach for different types of storm events will allow to define which spatial variabilities have to be sampled first and foremost, and therefore which are the crucial instrumentation efforts to provide.

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