Atmospheric Research 137 (2014) 14–24

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmos

Analysis of flash flood-triggering rainfall for a process-oriented hydrological model

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ARTICLE INFO

Article history:
Received 4 July 2013
Received in revised form 19 September 2013
Accepted 20 September 2013

Keywords:
Flash floods
Rain gauge
Radar
Catchment
Rainfall characterization
Regionalization

ABSTRACT

We propose an extended study of recent flood-triggering storms and resulting hydrological responses for catchments in the Pyrenean foothills up to the Aude region. For hydrometeorological sciences, it appears relevant to characterize flash floods and the storm that triggered them over various temporal and spatial scales. There are very few studies of extreme storm-caused floods in the literature covering the Mediterranean and highlighting, for example, the quickness and seasonality of this natural phenomenon. The present analysis is based on statistics that clarify the dependence between the spatial and temporal distributions of rainfall at catchment scale, catchment morphology and runoff response. Given the specific space and time scales of rainfall cell development, we show that the combined use of radar and a rain gauge network appears pertinent. Rainfall depth and intensity are found to be lower for catchments in the Pyrenean foothills than for the nearby Corbières or Montagne Noire regions. We highlight various hydrological behaviours and show that an increase in initial soil saturation tends to foster quicker catchment flood response times, of around 3 to 10 h. The hydrometeorological data set characterized in this paper constitutes a wealth of information to constrain a physics-based distributed model for regionalization purposes in the case of flash floods. Moreover, the use of diagnostic indices for rainfall distribution over catchment drainage networks highlights a unimodal trend in spatial temporal storm distributions for the entire flood dataset. Finally, it appears that floods in mountainous Pyrenean catchments are generally triggered by rainfall near the catchment outlet, where the topography is lower.

1. Introduction: context of the issue

The proximity of the Mediterranean Sea and the steep surrounding topography can foster the lifting of low-level flow in an unstable atmosphere, as for the Alps and Pyrenees (Cohuet et al., 2011; Davolio et al., 2009; Riesco Martín et al., 2013). The mesoscale factors leading to convection in a variety of forms, ranging from shallow to deep convection, are still poorly understood (Tarolli et al., 2012). Nuissier et al. (2008) examined the synoptic conditions with low-level moist warm air flow for three torrential rainfall events in the South-East of France, and more specifically the Aude region near the Pyrenean foothills and the Gard region. In the latter, precipitation varies enormously both in time and space. A study of flash flood-generating storms in the Italian Alps revealed extreme spatial gradients up to 80 mm km^{-1} in accumulated precipitation over 12 h (Norbiato et al., 2007). The combination of great variability in rainfall distribution and heterogeneous catchment properties can make hydrological processes variable and difficult to predict. According to (Tarolli et al., 2012), the accurate characterization of flash floods and their regimes is an important aspect of climate and hydrometeorological science. The authors show differences in

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0169-8095/$ – see front matter
http://dx.doi.org/10.1016/j.atmosres.2013.09.016

storm coverage, seasonality and hydrological characteristics between the North-Western and South-Eastern Mediterranean regions.

The North-Western Mediterranean region is prone to heavy rainfall, especially in autumn, often triggering severe flash floods. They represent one of the most destructive hazards in this region and have caused billion of euros of damage over the last two decades (Gaume et al., 2004). Llasat et al. (2010) point out the high frequency and impact of flash floods in the North-Western Mediterranean region with vulnerable urbanized and densely populated areas. Moreover, the steepness of numerous small catchments (of a few km^2) favours rapid concentration times, and the generation of runoff can suddenly turn into devastating floods. Water depth in the drainage network can peak within a few minutes or a few hours, and flash flood prediction and risk assessment still lack efficient procedures, mainly because these events are poorly monitored and understood (Marchi et al., 2010). Characterizing the response of catchments to intense rainfall may provide new and valuable insights into the hydrological processes involved and their dependency on certain catchment properties (Archer et al., 2007; Borga et al., 2008; Delrieu et al., 2005).

Several studies on flash flood characterization in Europe can be found in the literature. Gaume et al. (2009) inventoried selected events across Europe for seven large regions of 90,000 km^2 on average over the last six decades and analysed flood peak distributions. They noted that in Mediterranean Europe, floods generally occur in autumn, and are more violent than continental European floods, which are most frequent in summer. Parajka et al. (2010) analysed the differences in long-term rainfall regimes using seasonality indices across the Alpine Carpathian range (more than 200,000 km^2). Marchi et al. (2010) studied 25 extreme flash floods (60 drainage basins ranging from 9.5 to 1856 km^2) across Europe. The authors checked the relationship between catchment area and flood response time, and estimated flood wave celerity in order to adapt monitoring network capacities.

These previous studies focused on extreme flash flood response for catchments ranging from a few square kilometres to several hundreds of square kilometres within quite large study regions of around 100,000 km^2.

We propose a study of flash floods and their generating storm on the scale of the Pyrenean foothills and the Aude region (10,000 km^2), within which we selected 11 small- to medium-sized catchment areas ranging from 36 to 776 km^2 with contrasting properties. This study stands astride meteorology and hydrology. We shall therefore discuss hydrological, geomorphological and meteorological aspects of flood genesis. The innovative aspects of this study are the consequential dataset gathered, despite the difficulties involved in monitoring flash floods, and the multidisciplinary approach applied. From a hydrological point of view and in order to predict flash floods on a regional scale, we analysed a catalogue of more than ten years of flood data representing a total of 60 flash floods. The analysis is based on statistics that clarify the relationship between spatial and temporal rainfall distribution at catchment scale, basin morphology and runoff response. Rainfall indices describe the overall spatial organization of rainfall in terms of geographical location and dispersion, in relation to flow distance to the catchment outlet. Better knowledge about the dependency of hydrological processes on catchment properties is useful for tailoring physics-based hydrological models to specific regions and predicting floods in ungauged areas.

The paper is organized as follows. Section 2 describes the study zone and the methodology applied to data collection. The physiographical properties of the 11 catchments studied are detailed in Section 3. Finally, Section 4 characterizes rainfall fields and related catchment flood responses.

2. Study zone and data collection

The aim of the data collection methodology proposed by Marchi et al. (2010) was threefold: (i) to identify the most possible flash floods in various (responding) catchments, (ii) to collect high-resolution flow and radar rainfall data enabling the characterization/modelling of flood response, initial soil moisture status, and (iii) to collect data on the morphological properties of each catchment area (digital elevation model – DEM – at 25-metre resolution, source: IGN, the French mapping and survey agency), land use (Corine Land Cover), soil properties and geology (Fig. 4).

Our selection of flood events was based not only on specific peak discharge, but other criteria such as storm duration and catchment size. Like (Gaume et al., 2009), we selected catchments of under 1000 km^2, but unlike them, we did not limit storm duration to 34 h. Indeed, some multiple peak flows or longer rain events are of interest when studying the behaviour of catchments. Of the systematically recorded flood and rainfall data for the last decade, we chose to study all the strongest flood responses with specific peak flow over 0.2 m^3 s^{-1}km^2 for the selected catchments. The final catalogue for this study is composed of 11 catchments, representing a total of 60 flood events ranging from moderate flooding to major flash floods. Statistics are calculated for storm floods and indicate, for example, that three catchments respond simultaneously for a given storm (Table 1). The purpose is to analyse storm flood-generating mechanisms within a zone of a few hundred square kilometres. This data set contains flood events of different magnitudes. Thus, because of the variability of data, comments are often based on average statistics.

The literature contains several references about hydrological flood studies in the Spanish or French Pyrenees and related flood-prone areas (see, for example, (Gaume et al., 2004; Lajournade et al., 1998; Llasat et al., 2005)). The zone of interest for this paper is the eastern French Pyrenees, which is an area of particular interest for regional flash flood studies, providing a number of small to medium catchment areas (10–500 km^2) responding to the heavy rainfall frequent in this region. The Mediterranean climate zone is prone to heavy rainfall (Llasat et al., 2005; Molinié et al., 2011; Tramblay et al., 2011b) known as “cévenoles,” often occurring with a South or South-East wind over the foothills of the

Table 1
General statistics of the 60 selected storm flood events.

	Min.	Max.	Average	Stdev.
Rainfall duration (h)	14	101	43	18
Cumulated rainfall (mm)	30	317	133	61
Number of responding catchments for a given storm	1	9	3	2
Lag time (h)	3	15	7	3