

Answers to the reviewers comments  
“Multi-scale hydrometeorological observation and modelling for  
flash-flood understanding”  
by Braud et al.,

In the following, the reviewer comments appear in black italic and our answers are provided in blue.

**Referee#1 (D. Archer)**

*General*

*1) This paper gives a clear account of the monitoring philosophy to document the variability of active hydrological processes between and during flash floods from the hillslope scale to the regional scale. Although a suitable event has not yet occurred that will provide a comprehensive test for the developed network, the ambitious network and programme at all scales and at all stages of the hydrological cycle already provides suitable material for publication.*

Answer: We thank Dr. D. Archer for this positive appraisal of the paper content.

*2) However, I am concerned about the absence of a clear definition of a flash flood. The paper makes a distinction between ‘normal’ and ‘extreme’ behaviour in floods (p1876 C257 line 20). Does this imply that all extreme floods are flash floods? How would the authors distinguish between normal floods and flash floods given that there are many definitions of ‘flash floods’ (eg Douvinet and Delahaye, 2010). For example, did all 144 rain events having daily precipitation amounts greater than 190 mm during the 1958–94 period in southern France listed by Jacq (1994) generate flash floods – or did intense rainfall events of short duration of much lower total rainfall also generate flash floods on small to medium catchments. Is a flash flood characterised by the magnitude of its peak or by the rapidity of its onset (ie the rate of rise of the hydrograph)? (p 1874 line1). How rapid does the onset of the flood need to be categorised as a flash flood? Does the intense rainfall of the Mediterranean region require a different definition of a flash flood from those in more temperate areas as described by Douvinet and Delahaye ?*

Answer: These questions about the definition of a flash flood are very interesting. A clear definition of what we mean with “flash flood” is now included in the revised manuscript (**new lines 35-62**, see also answer to comment 2) of Referee#2).

Although several papers address flash floods, only few of them provide a definition of flash floods. Gaume et al. (2004) cite an IAHS-UNESCO-WMO (1974) definition of flash floods: “sudden floods with high peak discharges, produced by severe thunderstorms that are generally of limited areal extent” which is quite vague. In a further study compiling flash flood data across Europe, Gaume et al. (2009) write “... extreme flood events induced by severe stationary storms have been considered as flash floods. This relatively broad definition includes almost all the past events reported as flash floods in Europe, except dam break floods. The duration and spatial extension of the area affected by such floods depend on the causative storm and hence on the climatic setting. Most generally, the storms inducing flash floods lead to local rainfall accumulations exceeding 100 mm over a few hours (or more than 50 mm in less than 3 hours in northern France) and affect limited areas: some tens to some hundreds of square kilometres. Larger scale and longer lasting stationary storm events may, however, occur in some meteorological contexts, especially in the Mediterranean region. As

*an example, an area larger than 3000 km<sup>2</sup> received more than 300 mm rainfall within about 12 h on the 8th and 9th of September 2002 in the Gard region of France (Delrieu et al., 2004). On the basis of these considerations, it has been decided that the most extreme floods in watersheds of an area of less than 500 km<sup>2</sup>, generally induced by short duration storms (i.e. less than 24 h) should be considered as flash floods.”*

The definition we retain in our study is close to the Gaume et al. (2009) one, even if the catchments we consider are somehow larger (up to 2000 km<sup>2</sup>). This definition includes a wider set of events than the one proposed by Douvinet and Delahaye (2010), which consider what is also called “storm overflow runoff”, where the main processes are the combination of intense rainfall of short duration, high intensities and surface runoff with often erosive power. This type of flash floods is also characterized by their violent onset (in less than 1h) and high values of specific peak of discharges (up to 1m<sup>-3</sup>.s<sup>-1</sup>.km<sup>-2</sup>). The flash floods we are considering include this type of events but are not restricted to it. As mentioned by Gaume et al. (2009), the generating rainfall can also be long lasting rainfall (about 24h with moderate intensities but leading to accumulative rainfall of several hundreds of mm), which is quite specific of the Mediterranean region (see Delrieu et al, 2005 for a summary of their typical characteristics). In terms of dominant processes, the runoff can be explained by surface runoff in agricultural areas. In forested areas, due to the high infiltration capacity, estimated to be of several hundreds of mm/hr (e.g., Ayral, 2005), hortonian surface flow is seldom observed and sub-surface flow represents a significant contribution to the flood discharge (for example in the Valescure catchment in the paper). Hence the involved mechanisms are broader than those observed by Douvinet and Delahaye (2010) in the sedimentary areas. In terms of magnitude, Gaume et al. (2009) show that their European flash floods sample was characterized by specific peak discharge ranging from about 0.5 to 40 m<sup>3</sup>/s/km<sup>2</sup>. A specific peak discharge of this range is also considered necessary to speak about flash floods in our context, in addition to a quick rise of the flow (in a few hours).

To summarize, we retain the following criteria for the definition of a flash flood. The rise of the hydrographs should be very short (a few hours or less for catchments of 1-100 km<sup>2</sup> and less than 24h for catchments of about 1000 km<sup>2</sup>). To be considered as flash floods, the events must also have a significant peak discharge larger than 0.5 m<sup>3</sup>/s/km<sup>2</sup>.

Concerning the specific comment about Jacq (1994) study, we can provide the following elements. The inventory proposed by Jacq (1994) only concerns rainfall events. The document does not mention the associated damages or if they triggered flash floods. In addition, the inventory only deals with local gauge measurements, which is different from catchment rainfall. We would also like to underline the following points: 1/ intense rainfall events exhibit a high rainfall spatial and temporal variability; 2/ flash floods most often occur in ungauged catchments, so it is not always easy to know where a flash flood has occurred for a given event. It is likely that a flash flood occurs only in some part of a given catchment. Indeed, a rapid onset of the flood and a high peak discharge are more likely in small catchments than in larger ones. For instance Fig.14c shows that, during the November 9-10 2012 event, the specific discharge was larger than 0.5 m<sup>3</sup>/s/km<sup>2</sup> for the small 3.9 km<sup>2</sup> catchment but not for the larger ones.

*3) Were any of the events in autumn 2012 considered to be flash floods? If they were ‘normal’ was this because they did not produce exceptional peak flows or because they did not have rapid onset?*

Answer: In autumn 2012, there was no significant event with rainfall larger than 150mm in 24h in the study catchments (Ducrocq et al, 2013) over the period September 5 to November 6 2012. In addition, before the 9-10 November event which is discussed in the paper, soil

moisture was not high enough to induce a significant hydrological response. As illustrated in Fig. 14c, the catchment response was quick (a few hours), but the specific peak discharge was too low for the events to be considered as flash floods, except for some small catchments where it reached values larger than 0.5 m<sup>3</sup>/s/km<sup>2</sup>. But in any case, the response was not exceptional. A sentence has been added to the revised version to clarify this point (new lines 1389-1396)

4) *Given the availability of historical data (at least on rainfall) did they consider or calculate the risks of not getting a suitable event during the period of the project? Given the limited spatial extent of many flash floods is there particularly a risk that no events may occur on the three small catchments (Valescure, Tourgueille, Gazel) for many years.*

Answer: This question is interesting. For the preparation of the HyMeX 2012 Special Observation Period, a statistical analysis was performed to select the period with the highest probability of getting a rainfall event larger than 150-200 mm over the whole Western Mediterranean, but the same kind of study was not conducted for the study catchments. Nevertheless, the Valescure and Tourgueille catchments are instrumented since 2003 and 2008 respectively. In Valescure, significant events with specific peak discharge larger than 0.5 m<sup>3</sup>/s/km<sup>2</sup> were observed each year, with a maximum in October 2006 with a value of 3.2 m<sup>3</sup>/s/km<sup>2</sup>, which also destroyed the gauging station. In Tourgueille, the November 2011 event also destroyed the gauging station. The Gazel catchment has only been installed in 2010. In 2013, the 23<sup>rd</sup> October 2013 event, mentioned in section 4.3 of the paper also significantly affected the Gazel catchment, with a two-peak rainfall and a rise of the water level from 0.2 to 0.6m for the first peak and 0.2 to 1.4m for the second peak. So up to now, we have already registered in the various catchments (both historically and since 2012) interesting flash flood events in the small catchments. As the experiment is lasting two more years, we are confident that we will record other interesting events. In addition, as most of the experimental set up involves continuous measurements, we also record interesting events (not necessarily flash floods) during the whole years. These events also provide interesting insights on the active processes in various hydro-climatological contexts.

Some additional comments are also provided in the answer to comment 3) by Referee#2 and two specific sections were added in sections 1 (new lines 149-165) and section 2.1 (new lines 203-222), referring to the interactive responses to the reviewers comments.

#### *Specific comments*

5) *P 1879 line 9 et seq. With respect to hillslope monitoring, different network arrangements are made for the Gard and the Ardèche catchments on the basis of what are 'thought' to be the dominant modes of surface runoff. You should give some basis for this judgement or 'thought'.*

Answer: The answers to those questions are indeed provided in the introduction of section 2.2 p. 1878, and are based on previous experimental studies in the area, with similar geological and/or land cover. But it should be made clearer on p. 1879 and in the text.

Previous studies (e.g. Cosandey et Didon-Lescot, 1990; Tramblay et al., 2010) showed that sub-surface flow could be relevant for part of the Cévennes-Vivarais region (forested area and granite lithology like in the Valescure catchment). Infiltration/runoff field experiments (Ayrat, 2005; Marchandise, 2007) showed that the infiltration capacity of the top-soil was very high (a few hundreds of mm/hr) in the forested and granite lithology, generally excluding surface runoff as an active mechanism. For schist lithology, at the field scale, Brunet et al. (2010) also show the existence of soil saturation at the interface between the soil and the bedrock, but only ephemerally at the soil surface (Le Bourgeois et al., 2012). In cultivated areas in the region (mainly vineyards) other studies have shown that surface Hortonian runoff may also be

the dominant mechanisms (Hébrard et al., 2006; Nicolas, 2010). Clarifications appear in the revised [version in lines 246-249 and 256-260](#).

6) P1879 line 11 and 20 The word 'exposition' in French does not mean the same in English. Presumably 'exposure' is intended P1879 line 22 'shaley' Better simply 'shale'. In fact better shale lithology' and 'granite lithology'. P1882 line 2 repetition of 'soil' p 1887 line 10 'succion' is French. English is 'suction'. P1889 line 2 Spelling 'trough'

Answer: As suggested by Referee#2, "exposition" was replaced by "aspect" and the spelling errors corrected.

Concerning the lithology, we used "granite lithology" in the revised version of the paper. For the other lithology, we would like to underline the following point. Although there is only one word "schiste" in French, there exist two words in English:

- Shale is used to sedimentary rocks resulting from the successive deposit of clay (see <http://en.wikipedia.org/wiki/Shale>).

- Schist is used for metamorphic rocks which present sheet-like grains due to metamorphism (<http://en.wikipedia.org/wiki/Schist>). The geological formations encountered in the Cévennes, and in particular in the Tourgueille catchment are of this type. So we decided to finally keep the word "schists" in the revised version of the paper.

7) P 1890 line 29 Each class is considered statistically homogeneous what facilitates the study of its properties along agregation (Lepioufle et al., 2012). I don't understand this sentence! Reword.

Answer: The sentence is reformulated at follows in order to provide more detailed information. "Each class is considered as statistically homogeneous. For each class, the spatial structure of rainfall is estimated jointly on all time steps relevant to the class. In case successive time steps are within a same class, information is also gained about the temporal structure of the rainfall" ([see new lines 763-772](#))

8) P1892 line 9 'and a morphodynamical expertise of the site'. Please explain what this is.

Answer: We propose to modify the sentences as follows : "LS-PIV and SVR are non-contact techniques providing the flow velocity at the free-surface only, which requires the additional use of an appropriate depth-average to surface velocity ratio in order to compute discharge (see Le Coz et al., 2010, for a discussion of coefficient values). Also, a bathymetry cross-section profile must be determined based on pre and post-flood surveys. It is important to study the morphodynamical evolution of the stream during the flood in order to assess the additional discharge uncertainty due to possible bed changes." ([see new lines 818-820](#))

9) P 1902 line 28 'Nevertheless, low maximum peak discharges are recorded, as compared to historical values in both catchments (maximum peak discharge at the Ardèche at Sauze St-Martin recorded at about 4500m<sup>3</sup> s<sup>-1</sup>, and maximum daily discharge of 2510m<sup>3</sup> s<sup>-1</sup>). So, what were the comparative discharges during the event in m<sup>3</sup> sec<sup>-1</sup> ?

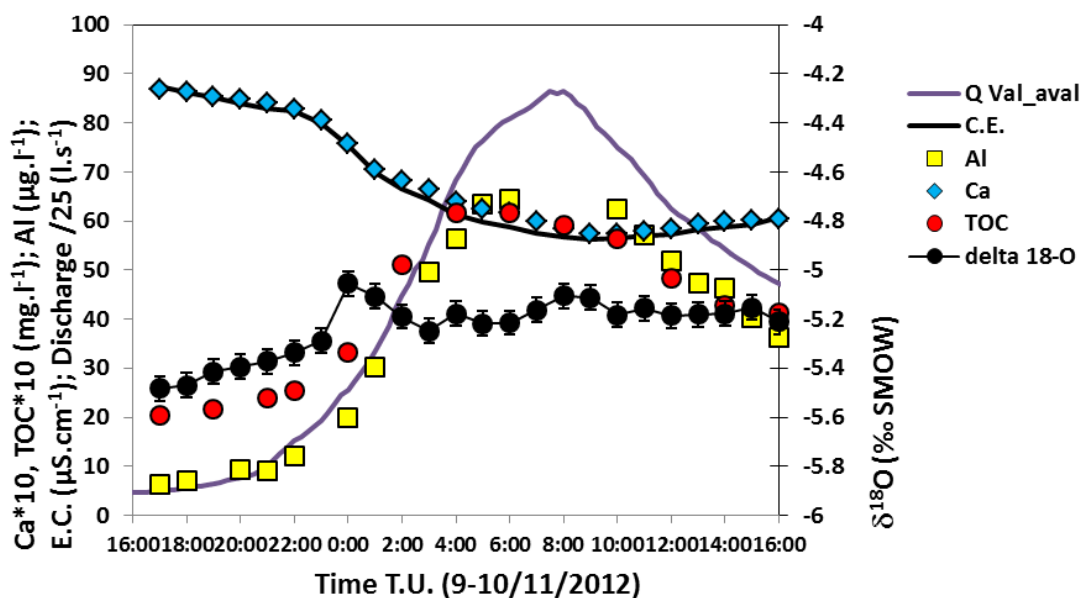
Answer: The value of the observed discharge can be seen in Fig. 9c, but it now explicitly mentioned in the text ([see new lines 1244-1249](#)). The maximum peak discharge observed at Sauze-St-Martin on November 10 2012 was 434 m<sup>3</sup>/s, so about 10% of the maximum ever recorded.

10) Page 1903 'Figure 11 shows the simultaneous behaviour of the electrical conductivity (EC), isotopic composition <sub>18</sub>O, Ca, Al and TOC concentration of the streamwater in the Valescure catchment (3.9 km<sup>2</sup>) during the 9–10 November 2012 flood event. You do not

comment on the fact that EC, Al TOC and CA appear to rise well before the main increase in discharge and peak before the discharge peak. Why is this?

All this section seems to refer to 'normal' flood events rather than flash floods. Under my own definition of flash floods, infiltration excess as well as saturation excess surface flow will occur during extremely intense short period rainfall. In this case the proportion of 'new' water is likely to be much higher. I.e., there is an intensity threshold over which the results for the normal modelled floods may no longer apply.

**Answer:** In the original figure, we were displaying the discharge from one sub-catchment and not the discharge at the outlet, which was missing due to sensor failure. We have updated the figure (see below) and the figure now displays a reconstructed hydrograph at the outlet of the Valescure catchment. The reconstruction method is the following: the discharge of the four upstream sub-catchments have been summed up after a translation using a constant velocity of 2 m/s. For the downstream sub-catchment, a rainfall-runoff model, previously calibrated on the catchment has been used. The increase of COT, Al, the dilution of Ca and the variation of CE are now more coherent in time with the discharges. About  $^{18}\text{O}$ , there is also a good synchronization with the discharges at the beginning of the flood, till 0.00 pm on the 10/11, but the isotopic composition then appears to be independent from the discharge. This is due to the fact that the isotopic composition of the rainfall changes between 9 and 10 pm, from nearly -2.5‰ to -5‰. This latter value is very close to the one of the stream a few hours later, so that variations cannot be detected anymore after this moment. In respect with the evolution of the geochemical decomposition, it is expected that a flood of major magnitude would bring different contributions in surface or sub-surface water flows at the outlet of the catchment. This information will be used for calibrating the hydrological processes with multi-variables control, such as discharges of course, but also geochemistry. Some sentences have been added in the revised version (new lines 1283-1304).



New Figure 11 : (Left) Time evolution of the Valescure streamwater electrical conductivity (E.C.), Calcium (Ca), Aluminum (Al), Total Organic Carbon (TOC) and discharge (Q) during the 09-10/11/2012 flood. (Right) Valescure streamwater isotopic composition ( $\delta^{18}\text{O}$ ).

## Referee#2

*1) This work describes a coupled observation and modelling strategy aiming at improving the understanding of processes triggering flash floods. The observation-modelling strategy is coupled in that the observations provide an input to the modelling framework, and the outcomes from the modeled events are used to improve the monitoring methods. Aspects of this strategy are illustrated for two Mediterranean French catchments (Gard and Ardèche), both larger than 2000 km<sup>2</sup>. The work is structured into three parts: 1) the experimental set up and the instrumentation; 2) the associated modelling strategy; 3) results obtained from the first year of observation and modelling work.*

*The topic is very interesting in that it provides a clear example of a coupled observational and modelling methodology: this coupling is central for the advancement of hydrology. The objectives are of great interest for the readers of HESS, and the writing is good (even though it should be improved at specific points – see below).*

*Nevertheless, the paper suffers from elements of structure and lack necessary details on some specific issues. The main element of structure concerns the requirement of linking the specificities of flash floods with the observational and modelling strategy. Often, these specificities are recognized and even addressed in the description of the monitoring methods; however, a section is missing where the characteristics of flash floods are described and where the logic of the observational/modelling strategy is illustrated as a consequence of these characteristics. I think that improving these elements of structure and reducing the length of the paper will make the already good work much more readable and impactful.*

*Considering the general interesting topic I think that the work might be publishable after moderate revisions. In the following I will try to outline, where and how the manuscript can be improved.*

Answer: We thank Referee#2 for this positive appraisal of the paper content and for his constructive suggestion to improve it. In particular, the introduction is rewritten so that the links between specificities of flash floods and the proposed observation strategy are better highlighted. In the introduction, following the suggestion of Referee D. Archer, a more complete definition of flash floods as considered in our study is also provided (see answer to comment 2)).

*2) 1. Linking the flash floods physical characteristics with the structure of the coupled monitoring/modelling approach.*

*This topic plays a role in the Introduction, but it is presented in a rather limited and scattered way, as if flash flood monitoring was only a question of contracted space/time scales and (consequently) of ungauged basins. These two elements are necessary elements, but not sufficient. There is a third element, in that flash floods are locally rare events. This is very important from a monitoring viewpoint, and has important consequences in terms of monitoring organization and observation risk within the given funding period. These two separate issues should be appropriately considered. Typically, events which are locally rare but not too rare within a monitored region, can be approached by means of opportunistic observations. This is clear to the authors, which have introduced an ‘on alert’ monitoring branch (Section 2.5) (perhaps using the term ‘opportunistic measurement’ instead of ‘on alert’ can make text more understandable). However, Section 2.5 arrives as a surprise within the story line. There is therefore a need to improve the layout of the Introduction, with a better linkage of process physics and monitoring organization.*

Answer: Following Referee#2’ suggestions, and taking into account remarks by the first Referee, the introduction has been completely rewritten. It now reads as follows:

“The Mediterranean area is prone to intense rainfall events, sometimes triggering flash floods that may have dramatic consequences (e.g. Ruin et al., 2008). Although several studies have addressed flash floods, understanding the processes leading to them is still an active research question. Before any further analysis, it is necessary to define what a flash flood is. Gaume et al. (2004) cite an IAHS-UNESCO-WMO (1974) definition of flash floods: “*sudden floods with high peak discharges, produced by severe thunderstorms that are generally of limited areal extent*” which is quite vague. In a further study compiling flash flood data across Europe, Gaume et al. (2009) write “... *extreme flood events induced by severe stationary storms have been considered as flash floods*”. They underline that flash floods are generally associated with intense rainfall exceeding 100 mm rainfall in a few hours affecting limiting areas (see also Douvinet and Delahaye, 2010). Nevertheless, they also point out that the generating rainfall can also be long lasting rainfall (about 24h with moderate intensities but leading to accumulative rainfall of several hundreds of mm), which is quite specific of the Mediterranean region (e.g. Delrieu et al, 2005). In terms of magnitude, Gaume et al. (2009) show that their European flash floods sample was characterized by specific peak discharge ranging from about 0.5 to 40 m<sup>3</sup> s<sup>-1</sup> km<sup>-2</sup>. In the following, we retain the following criteria for the definition of a flash flood. The rise of the hydrographs should be very short (a few hours or less for catchments of 1-100 km<sup>2</sup> and less than 24h for catchments of about 1000 km<sup>2</sup>). To be considered as flash floods, the events must also have a significant peak discharge, larger than 0.5 m<sup>3</sup> s<sup>-1</sup> km<sup>-2</sup>.

Such flash-flood events are characterized by space and time scales that conventional measurement networks of rainfall and river discharges are not always able to sample (Creutin and Borga, 2003; Kirchner, 2006). In addition, flash floods are locally rare events, so they are difficult to capture by field-based experiments (Borga et al., 2008). Borga et al. (2008) recommend the use of event-based and opportunistic observations, in particular post-flood surveys, to try to understand the processes leading to flash floods. A standardized method for post-flood field surveys was proposed by Gaume and Borga (2008) and Marchi et al. (2009). During the HYDRATE EU project (Borga et al., 2011), a significant effort was dedicated to the collection of hydrometeorological data on flash floods in Europe (Gaume et al., 2009; Marchi et al., 2010), leading to new insights into flash flood characteristics (Borga et al., 2010).

Spatial and temporal rainfall variability, landscape characteristics and soil humidity are recognised as important influential factors in flash flood generation (Borga et al., 2010). Several authors (Sangati et al., 2009; Anquetin et al., 2010; Viglione et al., 2010a, b) proposed methods to determine the spatial and temporal characteristic scales of the processes leading to flash floods. Borga et al. (2008) and Bouilloud et al. (2010) showed that high-resolution space-time rainfall fields provided by weather radars are essential to properly analyse and understand flash floods. Others authors showed the importance of topography (Norbiato et al., 2009), geology and soils (Anquetin et al., 2010; Braud et al., 2010, Martin, 2010), initial soil moisture (Borga et al., 2007; Le Lay and Saulnier, 2007; Gaume et al., 2009; Tramblay et al., 2010) or the impact of hydraulic routing within the river network (Bonnifait et al., 2009). According to the conditions, one or several factors can have a significant impact on the hydrological response. As a consequence, the predictability of such events remains low. In addition, this predictability is lowered by a high non-linearity in the hydrological response related to threshold effects (e.g. Rogger et al., 2012) and structured-heterogeneity at all scales (Blöschl and Zehe, 2005).

Then, assessing flash flood susceptibility and further understanding flash flood processes require a multi-scale and cross-combined hydro-meteorological approach. Furthermore, it is necessary to transfer the knowledge acquired at a given scale to another scale, the so-called change of scale problem (Blöschl and Sivapalan, 1995; Sivapalan, 2003a). Additionally, to

assess the risk everywhere, it is necessary to provide reliable hydrological simulations and predictions in ungauged basins (the PUB problem, see Sivapalan, 2003a, Hrachowitz et al., 2013) and at various scales (from a few km<sup>2</sup> to 1000 km<sup>2</sup>). Kirchner (2006) advocates field experiments, specifically designed to address the change of scale problem in order “to get the right answer for the right reasons” (Klemes, 1986; Grayson et al., 1992). The strategy is based on nested catchments, allowing the sampling of spatial heterogeneity at all scales (Sivapalan, 2003b). In addition, the emergence of new measurement tools (no-contact discharge gauging, geophysics, etc.), automatic sensors (soil moisture, limnimeters, geochemistry samplers) and high-resolution data such as remote sensing (weather radar, lidar DEM (Light Detection and Ranging Digital Elevation Model), satellite images) offers new perspectives in catchment monitoring. Examples of the use of this nested sub-catchment sampling strategy are the US CUASHI initiative (Reed et al., 2006) and the AMMA project (Lebel et al., 2009).

This study builds on these recommendations and is focused on the monitoring, understanding and modelling of flash floods in the Mediterranean context. It contributes to the Enhanced Observation Period of the HyMeX (HYdrological cycle in Mediterranean Experiment) program (Drobinski et al., 2013) and to the FloodScale project (<http://floodscale.irstea.fr/>). The two main scientific questions we are addressing are: 1/ how can we document the variability of active hydrological processes between and during flash floods from the hillslope scale to the regional scale? 2/ how can we describe and simulate the corresponding processes at the various scales?

To address these questions, the study relies on the collection of new data on flash flood and hydrological processes at all scales and their corresponding hydrological modelling. The experimental set up relies on multi-scale (nested sub-catchments) field-based observations, covering the regional scale (two catchments of about 2000 km<sup>2</sup>) complemented with opportunistic measurements during high intense rainfall events affecting those catchments. The nested sub-catchments are representative of the variability of landscape conditions in the Mediterranean region. The multi-scale approach allows the documentation of active processes at small scale, and how they aggregate at larger scales (Figure 1). The length of the experiment and the setting of continuous measurements allow the documentation of the “normal” catchment behaviour, as well as the “extreme” behaviour in order to capture potential threshold effects and/or abrupt changes in catchment functioning. From our experience (see Braud et al., 2014), the four-year duration of the experiment and the large area involved in the monitoring, ensures that significant events will be captured within the four-year duration of the monitoring on at least one of the small catchment. Long term time series from operational networks are also collected and analysed to get information about hydrological processes over longer time scales. Finally, innovative monitoring strategy for flash floods, relying on recent progress in instrumentation and sensors is proposed, complemented by opportunistic measurements to document discharges and soil moisture conditions during floods, as well as to perform geochemistry sampling to trace back water origin. Data analysis and models are combined in an iterative way (Figure 2) to increase our process understanding and modelling capability. In the particular case of flash floods, the collection of new data is of paramount importance, as flash floods are expected to trigger previously unobserved behaviours (Borga et al., 2008).” (see new lines 33-170)

Referee#2 suggests to use “opportunistic” observations instead of “on alert” observations. This is an interesting suggestion which has been retained for the revised version of the manuscript. Nevertheless, we would like to point out that the “on alert” term underlines the fact that a real time warning system is being deployed in autumns, based on the analysis of



information made available on the HyMeX SOP web site<sup>1</sup>. In autumn 2012, this task was done by professional meteorological forecasters from Météo-France (Ducrocq et al., 2013), but in 2013 and the other autumns, the forecasting is performed by non-professional volunteers from the FloodScale project, with the help of the AROME meteorological forecast, hydrological forecasts from operational services, as well as near-real time rainfall gauges and radar images data provided by Météo-France.

3) The authors should also provide some considerations about the likelihood of observing above threshold events within the given funding period (4 years), given a certain design threshold (Troutman and Karlinger, 2003).

Answer: The discharge time series are not long enough to perform the same kind of study as the one proposed by Troutman and Karlinger (2003). However, it is possible to use long series (1951-2003) of daily precipitation from three rain gauges located close to the three small catchments as a proxy for this assessment. Computing the frequency with which large precipitation events have been recorded by these three rain gauges should provide some order of magnitude for the likelihood of recording large discharge events on the three small catchments.

Figure 1 shows the annual probability of recording a precipitation event larger than  $x$  mm on any of the three rain gauges (estimated using observed frequencies). On any given year, the probability of recording a value higher than 150 mm is  $\sim 0.4$ , and decreases to  $\sim 0.2$  for 200 mm. However, over the 4-year project duration, these probabilities increase to  $\sim 0.9$  and  $\sim 0.5$ , respectively. The likelihood of recording precipitation values above 150 mm is therefore quite high over the project duration, which gives hope that flood events will also be monitored on the three small catchments. These elements have been added to the revised version of the manuscript (new lines 149-165 and 203-222, with reference to the published interactive comment)

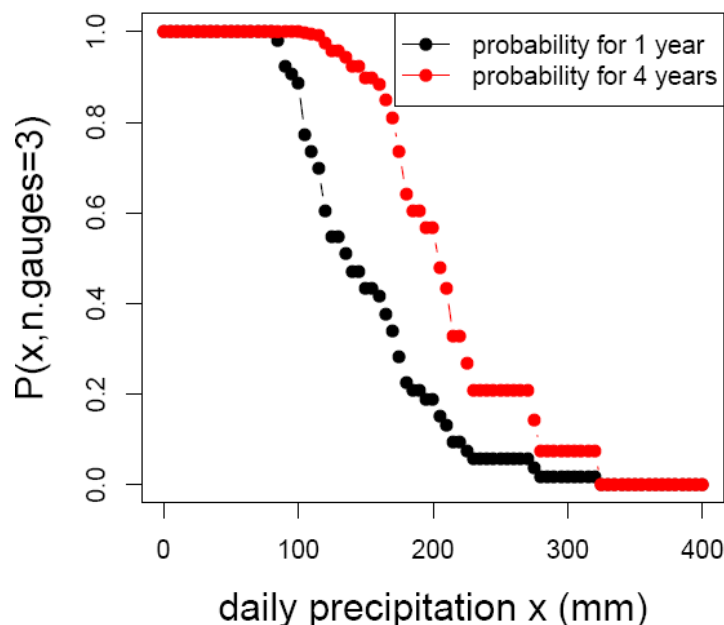


Figure 1: Annual probability of recording a precipitation event larger than  $x$  mm on any of the three rain gauges (estimated using observed frequencies)

4) There is also a need to clean the text by removing long and somewhat boring descriptions.

<sup>1</sup> <http://sop.hymex.org/>

*This is the case for two lengthy sections. The first is between P1873 L21 and P1874L15, where both the space-time scales of socio-economic impacts and of the flash flood processes are introduced. I think this is confounding, and the authors may rely only on the typical physical scales of the processes.*

Answer: The reference to socio-economic impacts has been removed and the introduction now focuses more on physical processes (see above).

*5) The second one is between P1875 L23 and P1876 L6, where the funding projects are presented. I think that this text can be strongly reduced.*

Answer: As suggested by Referee#2, this section has been reduced and now reads:

“This study builds on these recommendations and is focused on the monitoring, understanding and modelling of flash floods in the Mediterranean context. It contributes to the Enhanced Observation Period of the HyMeX (HYdrological cycle in Mediterranean Experiment) program (Drobinski et al., 2013), the FloodScale project (<http://floodscale.irstea.fr/>) and the Cévennes-Vivarais Mediterranean Hydrometeorological Observatory (OHM-CV, <http://www.ohmcv.fr> , (Boudevillain et al., 2011).” (new lines 136-144)

*6) 2. The role of radar observations*

*I was surprised to find radar observations relegated to the ‘large catchment’ section (both in Section 2.4 and in Fig. 2). I think this is not appropriate and not consistent with the large body of research work done with weather radar in this region. This work permits use of radar rainfall estimates as a cross scale information source. I think this type of information is also needed to assist the opportunistic measurements, which are not necessarily carried out at large scales and which needs rainfall estimates to be mechanistically evaluated and understood.*

Answer: We agree with Referee#2 that the role of radar data in our experimental set up is not highlighted enough. Radar data are also of great importance for small scale catchments (1-100 km<sup>2</sup>) in order to correctly interpret the spatio-temporal hydrological response, as underlined by Creutin and Borga (2003). Being able to have reliable information on the spatial variability of rainfall fields is also of importance for the correct interpretation of the limnimeter networks data, as already mentioned in the manuscript (section 2.3.2) and also recognized by an earlier work based on this type of network (Sarrazin, 2012).

During autumns 2012 and 2013 (and hopefully 2014), research radars were available on the Ardèche and Gard catchment in order to increase the spatio-temporal resolution of rainfall fields estimates (their location is provided in Figures 3 and 5 of the paper). Based on these data, and with the complement of the high density rainfall network called HPiconet (see Figure 5 of the manuscript), high resolution rainfall fields reanalyses will be conducted at resolution 0.0625 km<sup>2</sup> and 15 minutes time step (as compared to 1 km<sup>2</sup> resolution and 1h time step for the reanalyses at the larger scale – see section 4.4 of the manuscript).

A mention of the importance of high resolution rainfall information for data analysis and modelling of small scales catchments has been added to section 2.3 of the revised manuscript (new lines 561-568 and 1414-1419).

In addition, radar rainfall were also really useful during what is called “on alert” observations in the manuscript. Indeed, during autumns 2012 and 2013, near real time radar images, together with rainfall gauges data were available to the meteorological forecasting team. Once teams had been sent on the field to perform discharge gauging or “opportunistic” measurements, the radar images were very useful to guide the teams in areas where rainfall was the most significant. This point will be added to the revised version of section 2.5 (new lines , 854-869).

7) 3. *More precision required at some instances.*

*Dominant processes: the monitoring methodology is carried out in different ways accordingly with the presumed local runoff generation dominant process. Two dominant processes are considered: infiltration excess and saturation excess (see for example P1879 L9). I think that at least a reference to the methodology used to map the dominant runoff generation should be provided here.*

Answer: The knowledge about dominant hydrological processes in the various areas comes from previous studies in the Cévennes-Vivarais region. Previous studies (e.g. Cosandey and Didon-Lescot, 1990; Trambly et al., 2010) showed that sub-surface flow could be relevant for part of the Cévennes-Vivarais region (forested area and granite lithology like in the Valescure catchment). Infiltration/runoff field experiments (Ayrat, 2005; Marchandise, 2007) showed that the infiltration capacity of the top-soil was very high (a few hundreds of mm/hr) in the forested and granite lithology, generally excluding surface runoff as an active mechanism. For shale lithology, at the field scale, Brunet et al. (2010) also show the existence of soil saturation at the interface between the soil and the bedrock, but only ephemerally at the soil surface (see also Le Bourgeois et al., 2012). In cultivated areas of the region (mainly vineyards) other studies have shown that surface Hortonian runoff may also be the dominant mechanisms (Hébrard et al., 2006; Nicolas, 2010). Based on this previous knowledge, the three pilot sites were chosen as follows: two sites in forested areas on two different geologies where sub-surface runoff was suspected: Valescure (granite lithology) and Tourgueille (shaley lithology); one site in an agricultural area (Auzon-Claduègne-Gazel site, with basalt and limestone geology). In addition, this latter catchment was chosen in an area where the annual pluviometric gradient is large (Molinié et al., 2012), in order to highlight the effect of rainfall spatial variability, which is continuously documented using the Hpiconet dense rainfall network.

In addition, an exploratory study was conducted using the IRIP (Indicator of Intense Pluvial Runoff) method (Dehotin and Breil, 2011) to provide maps of areas prone to the generation and accumulation of runoff respectively (Bonnet, 2012) to get maps at the scale of the whole Cévennes-Vivarais region. Further verifications on the validity of the IRIP hypothesis method are still needed before possible publication of the maps.

Clarifications appear in the revised **version in lines 246-249 and 256-260**.

8) *Moreover, by virtue of the intensities associated to flash floods, runoff generation dominant processes may change. The authors should address this specificity.*

Answer: We agree with Referee#2 on this point. Sometimes, rainfall intensities can be very high leading to surface runoff even in areas classified as “prone to sub-surface runoff”. In addition, rocks are sometimes encountered at the surface, which leads to surface runoff, whatever the rainfall intensity. Some sentences have been added in the revised version of the manuscript (**new lines 268-274**).

9) *Part of the hillslope monitoring net is periodically dismantled and moved to another place (P1879, L18). The motivations for this procedure should be reported.*

Answer: This choice relies on the hypothesis that one hydrological year is enough to sample both dry and humid conditions, and determine the response time of soil moisture as well as the associated soil hydraulic properties. The analysis of the collected data is part of a PhD thesis in progress, and first results obtained by inversion of the Richard's equation (Le

Bourgeois et al., 2012) are promising. This point is now explained in the revised version (new lines 308-312).

10) *Role of karst aquifer. Karst specific processes are well known to influence flash flood dynamics (Delrieu et al., 2005; Zanon et al., 2010), and are well represented in the Gard region (Delrieu et al., 2005). However, karst processes are not specifically considered in the monitoring and modelling strategy. The authors should provide a comment on this decision.*

Answer: Referee#2 is right in saying that karst processes are not central in our monitoring and modelling strategy, although not fully absent. Indeed, as mentioned in section 2.3.1, one gauging station of the Avène catchment installed in 2013, is controlling a 10 km<sup>2</sup> catchment mainly consisting in carbonated deposits (karstic areas). In addition, in the Cévennes-Vivarais region, several operational gauging stations from the Banque Hydro<sup>2</sup> data base are draining karstic area. The Medyciss<sup>3</sup> observatory is also dedicated to karstic areas and involves teams specialized in this type of rocks. We have made the choice to rely on the knowledge provided by such teams to get observations and modelling tools relevant to the karstic areas included in our catchments of interest (e.g. Coustau et al., 2012). In our study, karstic areas are also taken into account in data analysis (e.g. Vannier et al., 2013) and in the modelling. For instance, the approach developed by Adamovic et al. (2014a) and mentioned in section 4.4 has been extended to the whole Ardèche catchment, which includes karstic areas (Adamovic et al., 2014b). For this purpose, data from the Banque Hydro have been used.

Some sentences about karstic areas have been added in section 2.2.1 (new lines 516-522).

*Specific comments.*

11) P1874 L8: *'flash flood studies': studies is perhaps inappropriate here, and a more correct term is predictions.*

Answer: The sentence has been removed in the revised version.

12) P1883 L29: *connection instead of connexion.*

Answer: This has been corrected.

13) P1884 L20: *I wouldn't say that current meter is limited to small streams and small discharges.*

Answer: Referee#2 is right. The sentence has been modified as follows: "Traditional salt dilution, current meter methods or hydro-acoustic profilers are used for low to medium discharges, and for floods in small streams only. When higher velocity and flow depth, as well as floating debris are present, this put in danger the operators and the sensors. This typically occurs during floods in medium to large streams. In this case, modern non-intrusive methods, such as SVR (see Sect. 2.5.3) are deployed." (see new lines 531-539)

14) P1888 L16-20: *The text about the fractal approaches is completely disconnected from the rest of the section and is meaningless. Please remove it.*

Answer: The text has been removed and partly incorporated into the sentences about data mining (see next point).

15) *Data mining: One of the building blocks of the paper is that flash floods are poorly observed flood events. Therefore I think that the emphasis given to the 'data mining techniques', made at P1888 L12 and at P1889 L3, should be nuanced.*

Answer: This has been corrected and the sentence now reads: "Bayesian networks (e.g. Maes et al., 2007) as well as fractal analysis based on lidar DTM (Martin et al., 2013) are also tested for better flash flood understanding,. The analysis particularly focuses on identifying whether the relationships between observed factors at one scale are identical at other scales and if

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<sup>2</sup> <http://www.hydro.eaufrance.fr/>

<sup>3</sup> <http://www.medycyss.org/>

fractal approaches can provide invariant descriptors which can be compared between catchments (Forriez et al., 2011).” (see [new lines 664-671](#))

16) P1889 L11: ‘exposition’ here and in other places, should be ‘aspect’.

Answer: “Aspect” has been used in the revised version of the paper.

17) Fig. 2: This figure is interesting, but rather generic. Which is the place of flash floods within this figure?

Answer: Referee#2 is right in saying that the figure is generic and the synergy between observation and modeling can be used to address lots of questions in hydrology, and even beyond hydrology. In the particular case of flash floods, the collection of new data is of paramount importance, as flash floods are expected to trigger previously unobserved behaviours (Borga et al., 2008). A sentence has been added in the introduction (see [new lines 167-170](#)).

18) P1910: Martin Caliano should be Martin Calianno.

Answer: This has been corrected.

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