# Reply to Interactive comment on
# “Multi-scale hydrometeorological observation and modelling for flash-flood understanding”
# by Referee#2

I. Braud et al., April 2014

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

*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 km2. 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 tank 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 below).

*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 $m^3 s^{-1} km^{-2}$. 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 $km^2$ and less than 24h for catchments of about 1000 $km^2$). To be considered as flash floods, the events must also have a significant peak discharge, larger than 0.5 $m^3 s^{-1} km^{-2}$.

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 hydrometerological 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$^2$ to 1000 km$^2$). 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$^2$) 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)."

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[1]. 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 from Météo-France , hydrological forecasts from operational services, as well as near-real time rainfall gauges and radar images data provided by Météo-France.

*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 ~ 0.4, and decreases to ~ 0.2 for 200 mm. However, over the 4-year project duration, these probabilities increase to ~ 0.9 and ~ 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.

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[1] http://sop.hymex.org/

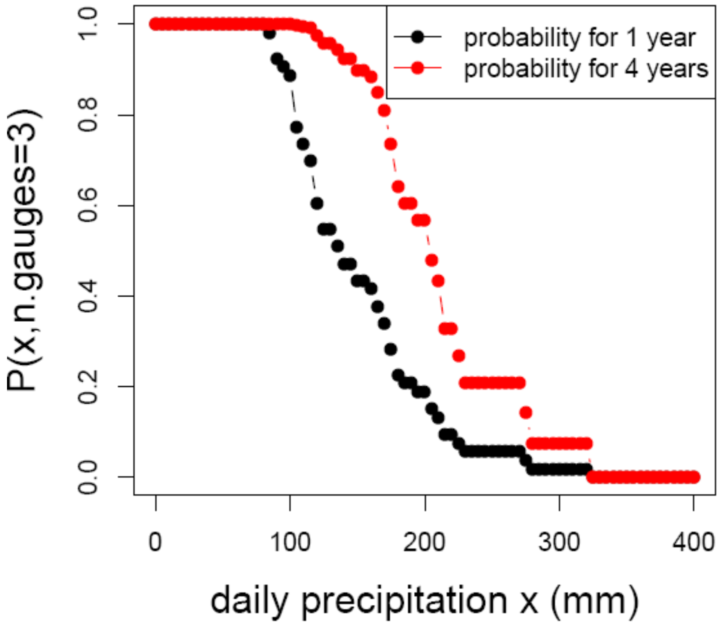

*Figure 1: Annual probability of recording a precipitation event larger than x mm on any of the three rain gauges (estimated using observed frequencies)*

*There is also a need to clean the text by removing long and someway boring description. 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).

*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) and to the FloodScale project (http://floodscale.irstea.fr/)."

*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 $km^2$) 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$^2$ and 15 minutes time step (as compared to 1 km$^2$ 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 will be added to section 2.3 of the revised manuscript.

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.

*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; 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 (Ayral, 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 dominant 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 (see also Le Bourgeois et al., 2012). In cultivated areas of the region (mainly vineyards) other studies have shown that surface Hortonian runoff may 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 (schist 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., 2011), 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. This is work in progress and further verifications on the validity of the IRIP hypothesis method are still needed before possible publication of the maps.

*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 will be added in the revised version of the manuscript to highlight this point.

*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.

*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, karts 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$^2$ catchment mainly consisting in carbonated deposits (karstic areas). In addition, in the Cévennes-Vivarais region, several operational gauging stations from the Banque Hydro[2] data base are draining karstic area. The Medyciss[3] observatory is also dedicated to karstic areas and involves teams specialized in this type of geological formations. 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.

*Specific comments.*
*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.
*P1883 L29: connection instead of connexion.*
Answer: This has been corrected.
*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

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[2] http://www.hydro.eaufrance.fr/
[3] http://www.medycyss.org/

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."

*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).

*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 fractal approaches can provide invariant descriptors which can be compared between catchments (Forriez et al., 2011)."

*P1889 L11: 'exposition' here and in other places, should be 'aspect'.*

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

*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).

*P1910: Martin Caliano should be Martin Calianno.*

Answer: This has been corrected.

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