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Multiscale modelling of rainstorm-induced historical intermediate floods (June–November) in the Rhone River Basin

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Abstract This study reveals the changes and evolution of rainstorm-driven intermediate floods occurring and driving multiple damaging hydrological events in the Rhone River Basin (RRB), since 1500 until 2010. A parsimonious approach was developed to simulate the major hydroclimatological flood-producing forcing, the Multiscale Rainstorm Climate Model (*STORMCLIMM*). We collected the frequency of intermediate floods—a type of particularly hazardous floods commonly taking place between June and beginning of November—from the RCB to be compared to *STORMCLIMM* estimates. The latter, smoothed by a moving window of 21 years, results in a high-pass filter in the time domain, which magnifies the signal of forcing variations causing intermediate floods. The RRB showed large temporal variations in both extreme rainstorms and associated multidecadal intermediate-floods (MUDIF) frequency at different climatic periods and land-use systems through historical times. An important peak was observed in the Maunder Minimum (1645–1715 AD). The model allowed detecting MUDIF occurred in the historical times. The situation becomes interesting with respect to recent times, because the Rhone landscape looks more vulnerable in the last decades as a consequence of land-use changes and climate shift towards more erratic and intensive storms. This evidence suggests that the interactions of land-use and climatic changes may turn into considerable vulnerability to fluvial flooding and agro-ecosystem connected to them for upcoming years. The Rhone, for example, provides basis for use of hydrological indicators (such as the one represented by *STORMCLIMM*) for one site or region and which, through minor modifications, can be made relevant to specific needs.

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1 Introduction

Landslides, floods and secondary floods triggered by rainfall and causing extensive damage are collectively known as Damaging Hydrogeological Events (DHEs), defined as the occurrence of one or more simultaneous phenomena (Petrucchi and Polemio 2003, 2009). Due to the simultaneous triggering of various types of phenomena, DHEs can be treated as a source of multiple hazards (AA.VV. 1983). Multiple damaging hydrological events (MDHEs, after Diodato et al. 2012) are triggered by either short and intense storms or longer duration rainfalls (Grove 2001). They develop flooding, erosion, downpours and other phenomena affecting human habitats and ecosystems (Diodato 2010). The impacts they may have on cropland productivity and environmental services demand information about climate forcing-response relationships to explain MDHEs across a wide range of interconnected temporal and spatial scales (Clarke and Rendell 2005; Schad et al. 2011). European countries since historical times have experienced extreme rainfalls, which have often been accompanied by an exceedance of the drainage capacity in flood-plain areas (Glaser et al. 2010). There is large natural variability in the intensity and frequency of mid-latitude rainstorms that drive MDHEs such as floods, mudflows and accelerated soil erosion. The occurrence of exceptionally heavy rainfall events and associated floods, sediment and organic carbon fluxes in many European areas during recent decades (Gaume et al. 2009; Llasat 2001) motivated us to study long-term changes in extreme precipitation forcing and associated impacts in the basin of Rhone, historic river of France and Switzerland (hereafter indicated as RRB).

The floods that are in the focus of this paper are “extraordinary flooding” (or intermediate floods) which, for their disruptive activities, are particularly hazardous events. Intermediate floods occur when the precipitation discharge concentrates in few hours to 1 day. They are also known as “catastrophic flash floods” of type 2a, distinguished by “extraordinary flash floods” (type 1), when a flood is produced by an intense and short-rainfall event, and “catastrophic floods with flash floods” (type 2b), when rivers overflow their usual channels. This classification scheme is from Barrera et al. (2005, 2006). Other classification systems, which are also used (e.g. Dartmouth Flood Observatory, <http://floodobservatory.colorado.edu>, cited by Esposito et al. 2011), turn up with the same meaning: “small floods” (class 1), “intermediate floods” (class 2) and “catastrophic or large floods” (class 3). Intermediate floods are events with duration of less than 24 h, and the maximum precipitation is usually recorded in less than 6 h, with accumulated rainfall of nearly 200 mm. They are strongly convective events and can produce catastrophic flash floods in rivers of pre-littoral rainfall origin with modest basins and flows (50–2,000 km²), simultaneously with the maximum rainfall as well as short water courses. When intermediate floods happen, the river flows are generally sufficient to overflow the usual channels, and water is present in the streets or sectors under study. Intermediate floods may produce the highest number of casualties when they affect flood-prone areas with high concentrations of people (Barrera et al. 2006). Damage to hydraulic installations adjacent to or in the channel, such as mills, irrigation channels, dams or foot-bridges, can be severe, with partial destruction (Matos Silva 2011). Intermediate floods have represented the most destructive natural hazard in France over the last two decades, causing around one billion euros worth of damage (Gaume et al. 2009; Braud et al. 2010).

Several efforts have been undertaken towards the reconstruction of flood events at European continental scale (EXCIMAP 2007; Glaser et al. 2010), French regional scale (IFEN 2006; Météo France, through <http://www.meteofrance.com>) and specific basins such as the RRB (Miramont and Guilbert 1997; Arnaud-Fassetta 2003; Bianciotto 2005; MEDAD 2006a; PLANRIN 2006; Anquetin et al. 2009). The latter works raised the importance of having comprehensive catalogues of MDHEs for the RRB or its sub-basins. However, in these studies, a clear and homogeneous meteo-hydrological forcing was not assumed, with the exception of Pichard (1995), who studied a limited sector of the RRB around Arles (43.68 latitude North; 4.63 longitude East).

Changes in rainfall amount associated with changes in storm rainfall intensity likely have a greater impact on the homogeneity of natural damaging hydrological events than simply changes in rainfall amount alone. Intermediate flooding also involves the surface response to precipitation, such as rainfall–runoff relationship, surface processes and flood-routing mechanisms (Stephen and DeGaetano 2008). For regional frequency analysis of hydrological variables, a rainfall index is generally mapped at given location for later developing a rainfall surface over the region (Bobee and Rasmussen 1995). However, despite its relevance in risk assessment and hydraulic structure design, little attention has been paid to the problem of spatial evaluation of rainfall indices, often solved through purely statistical methods adapted to each test-case (Boni et al. 2008). So, it is also because the temporal succession of pulsing rainstorms is complicated by factors including the climate under which the storms occur, the localized nature of the events and inconsistency in spatial and temporal resolutions of observational and modelled data. For instance, an operational issue and a requirement for rainfall–runoff erosivity modelling in climate-change studies are the access to long records of sub-daily rainfall. In Europe, they are available for few locations only, such as Ukkel (Verstraeten et al. 2006), central Italy (Gozzini et al. 2007) and Portugal (De Lima and de Lima 2009). The interest on this topic has induced developing parsimonious approaches to model ungauged and gauged basins with low data requirements, especially the smallest ones, which are recognized as the most vulnerable to rainstorm-driven flash and intermediate floods (Ruin et al. 2008).

For the RRB, purpose of this paper is to investigate the association between temporal multiscale patterns of rainstorms and multidecadal intermediate-flood (MUDIF) mean frequency over a long period (1500–2010) encompassing the Little Ice Age (LIA, 1300–1850 AD) until recent times. For relatively homogeneous areas, this association allows inferring the importance of intermediate floods produced by the most precipitation-relevant descriptor variables. For example, summer flash floods in Europe may be a consequence of convective rainfalls, whereas synoptic rainfalls (or a combination of both synoptic and convective rainfall processes) tend to be more important for flood generation in autumn (Merz et al. 1999). Although it is not possible to directly relate individual heavy rainfall events to flood types, knowledge of the frequency and distribution of monthly or seasonal rainfall can help to better define the potential predictors for cumulative intermediate floods spanning over long time periods. The paper thus focuses on developing a parsimonious hydrological model (*STORMCLIM*) suited to bring the observed proxy variations of MUDIF over historical times in the RRB. In particular, the *STORMCLIM* developed in this study incorporates few of relevant variables such as seasonal precipitation and geographic data that are able to capture climatic variability in the study catchment and are easily available nowadays via, for instance, web resources. A model with these characteristics is particularly useful to reconstruct the variability of intermediate floods back in time over periods in which only seasonal precipitation rates are available.

2 Study-area and modelling approach

2.1 Study-area

The Rhone River (813 km) originates in the Swiss Alps (Rhone Glacier, 46.57 latitude North; 8.38 longitude East; 1,765 m a.s.l., Fig. 1a) and runs from there through south-eastern France for 550 km before entering the Mediterranean Sea.

In France, the Rhone River Basin (RRB, Fig. 1b) extends from the area north of Dijon (47.29 latitude North; 5.04 longitude East) to the Camargue, the region located south of Arles (43.68 latitude North; 4.63 longitude East) and west of Marseille (43.30 latitude North; 5.37 longitude East), between the Mediterranean Sea and the two arms of the Rhone River delta. The total area of the river basin is 98,000 km², of which 90,000 km² in France. The influence of Mediterranean circulation causes a distinct regional pattern in the seasonality over the complex orography of the RRB (Fig. 1b). The annual precipitation across France ranges between about 600 and 1,000 mm in the plain and hills, respectively, up to 1,500 mm in the eastern mountain areas. A high interannual variability is observed as consequence of the alternation of dominant atmospheric patterns. Rainfall temporal and spatial variability is high as is the case of Western Europe regions, where the most extreme events take place (Romero et al. 1998). The westerly regions of Europe are under the strong influence of Mediterranean convective cellules and orographic precipitations (Llasat 2001). This causes overland flows and erosive rainfalls with more heavy rains, especially across southern and eastern France (Fig. 1a).

As observed in Fig. 1a (little rectangular area), the RRB is included in the core area with the highest 95th percentiles of June–November daily rainfalls in Europe. In this basin, the most extreme storm events are induced by instabilities produced by the confrontation between the cold air masses brought from the North and the Mediterranean warm air

Fig. 1 a Heavy precipitations in Europe corresponding to the 95th percentiles of daily rainfall in June–November for the time period 1957–2002 (ERA-40 database, <http://www.ecmwf.int/research/era/do/get/era-40>, mapped via Climate Explorer, van Oldenborgh et al. 2009), b Rhone River Basin with the main towns

(after Parajka et al. 2010), which result in both summer precipitation maxima (showers and downpours) and typical schemes of autumn mesoscale precipitations (rainstorms and thunderstorms). In this way, rainstorms can be associated with the floods of type 2a (also known as intermediate floods) described in Barrera et al. (2006).

2.2 Data sources

The reconstruction work of the hydrometeorological scenario represented by the intermediate floods occurred in the RRB since 1500 was performed in three steps. First, we searched for and collected historical datasets, in particular on compilations of documentary data by Pichard (1995), Miramont et al. (1998), Antoine et al. (2001), MEDAD (2006b), and by web-based resources (Portail de revues en sciences humaines et sociales, http://www.persee.fr/web/revues/home/prescript/article/rga_0249-6178_1919_num_7_1_4739; Pôle Alpin d'études et de recherche pour la prévention des Risques Naturels, http://www.risknat.org/pages/programme_dep/docs/lthe/2008_Obled-jan2010.pdf; HYDRATE project, <http://www.hydrate.tesaf.unipd.it/index.asp?sezione=FFDCPresentation>). Second, the use of these sources made it possible to reconstruct damaging hydrological events and interpret them in terms of flood types. We created records to document each flood event mentioned in the evidence, where a flood describes an event that matches the criteria by Barrera et al. (2005, 2006). As an example, Fig. 2 is a matrix-style monthly hydrological report by Pichard (1995) for the period 1700–1800. Black cells reflect intermediate floods over May–November. Floods occurred from December to April were excluded from the present study because associated with the frontal rainfall and snowmelt, which are not pertinent with intermediate-flood characteristics (Radziejewski 2011). Third, the recorded intermediate floods (785 over 1500–2010) were accumulated at multidecadal scales by a moving average window during established climatic periods. The intermediate-flood data of the RRB were associated with the multidecadal storm erosivity with a high-pass filter signal.

Seasonal precipitations were used to input data into the climate model of rainstorm variability represented by Eq. (1) (sub-Sect. 2.3). They were obtained, for the RRB, from the reconstructions for European land areas (30° West to 40° East/30°–71° North, on a $0.5^\circ \times 0.5^\circ$ resolved grid) published by Pauling et al. (2006) and available online (<http://www.ncdc.noaa.gov/paleo/pubs/pauling2006/pauling2006.html>). The averaging of 10 grid-point data extracted across the RRB was applied to characterize an areal mean

Fig. 2 Table of climatic events occurred in the Rhone River Basin between 1700 and 1800, extracted from Pichard (1995). Horizontal lines are months from January (bottom line) to December (top line). The basis for the creation of a dataset of intermediate floods comprises floods of more than 4 m of water, represented by black cells over May to November

rainfall. Spreadsheet-based assessment of the *STORMCLIMM* was performed, with the graphics and display support of a web statistics software (Wessa 2011).

2.3 Generation of extreme hydrological events

The use of nonlinear indicators of rainstorms is supported by the empirical evidence that nonlinearities are involved in the dependence of rainfall-runoff erosivity on rain intensity (D'Odorico et al. 2001). In this study, we have employed the same principle of Diodato and Bellocchi (2012) to expand a solution in which seasonal rainfall quantiles and overland flows are modelled together to account for temporal dependence of rainfall-runoff erosivity index; and although the Multiscale Rainstorm Climate Model (*STORMCLIMM*) was not specifically designed for rainfall-erosivity estimation, the output of the *STORMCLIMM* (Eq. 1) is meant to provide values compatible with the climate *R*-factor of the Universal Soil Loss Equation by Wischmeier and Smith (1958) and revised by Foster et al. (1977).

It is assumed that a large quantile value of the seasonal precipitation distribution over a bidecadal time (21 years) is able to deliver adequate amounts of erosive storms in summer, while runoff is predominant in autumn (after Diodato et al. 2012). This is also in agreement with the results referred by Hydrate database (Gaume et al. 2009), revealing the predominant role played by erosive rainfall in explaining extreme events across the summer and autumn seasons. Based on this understanding, extreme rains are captured by percentile statistics during the spring to autumn seasons. In particular, accumulated occurrence and magnitude of extreme rain events over multiple decades are controlled by the combination of meteo-climatological conditions and hydrological factors and revealed by a high-pass filter in order to amplify interannual climate signals. The conceptual model was thus resolved into a nonlinear equation with parsimonious structure:

$$STORMCLIMM_{(Y)} = \alpha \cdot \sqrt{prc50 |P_{Spr}|} \cdot F_{(Y)} + \lambda \cdot (prc95 |P_{Sum-Aut}|)^{\eta} \quad (1)$$

where $STORMCLIMM_{(Y)}$ is the rainstorm climate index estimated for the year Y ; $F_{(Y)}$ is a 1-year pulsing component (mm), set equal to the summer rainfall total for the current year ($P_{Sum(Y)}$) and behaving as a high-pass filter; $prc50 |P_{Spr}|$ (mm) is the 50th percentile of the spring rainfall total for each bidecade (with the Y th year centred on a period of 21 years, including the 10 years before and the 10 years after Y); $prc95 |P_{Sum-Aut}|$ (mm) is the 95th percentile of the summer (June–August) and autumn (September–November) rainfall totals over the bidecade; α and λ equal to 0.1 and 1.0, respectively, are scale parameters which make the two terms of Eq. (1) comparable in size, and the output compatible in magnitude with the (R)USLE *R*-factor; η is a shape term depending on the geographic location, in the following form:

$$\eta = \beta + \gamma \cdot LAT + \delta \cdot LONG \quad (2)$$

where LAT (°) and $LONG$ (°) are site latitude and longitude, respectively; β is a shift parameter (a virtual value of η at the point at which the equator and the prime meridian intersect); γ (°⁻¹) and δ (°⁻¹) are scale parameters. The values from Diodato and Bellocchi (2012) were used for the parameters of Eq. (2): $\beta = 2.24$, $\gamma = -0.0226574$, $\delta = -0.00477392$.

The structure of Eq. (1) suggests that, if seasonal precipitations on bidecadal time scale— $prc95 |P_{Sum-Aut}|$ —are important factors to explain annual rainstorms, the antecedent soil moisture— $prc50 |P_{Spr}|$ —also contributes to explain the intensity of the

response, and high-pass filtering is assured by introducing summer rainfall total— $P_{\text{Sum}(Y)}$ —for the current year (Y), in order to amplify interannual variability.

Relatively high precipitations over summertime are suitable predictors of intensive floods occurring in the year for which the estimate is made. In keeping with the concept of developing a sequence of rain events that can generate floods across the basin over decadal time scales, the 50th percentile of the spring precipitation record was judged to be sufficient. In fact, the 50th percentile of the spring rainfall total is a proxy for antecedent soil humidity before intermediate-flood occurrence, the latter being largely dependent on the rains occurring in summer and autumn. Heavy storms causing floods are expected to be more frequent during the wet season (autumn). Nevertheless, during the wet season, dry periods are also possible, and some floods can behave as they would belong to the dry season. During the dry season (summer), the intensity of precipitation and even the rainfall recorded can be higher than during the wet season, but floods are not necessarily the main outcome. However, some dry season floods can occur after several days of rainfall, and their behaviour is similar to those occurring during the wet season (García-Ruiz et al. 2005). Under dry conditions represented by summer months, fast though limited hydrological responses generally occur, even during important rainstorm events, thus suggesting that overland flow may be generated in small parts of a basin, close to the channels (Seeger et al. 2004). Under wet conditions represented by the fall season, the response may also be fast, but the peak flow is much higher, even during moderate rainstorm events, which suggests an enlargement of the runoff-generating areas (Dunne and Black 1970; Gallart et al. 2002).

3 Results

3.1 Evaluation of *STORMCLIMM*

Standard calibration of the *STORMCLIMM* (Eq. 1) was not practical due to inadequate monitoring and differences in the nature of hydrological data. As an alternative, we have taken into account the decadal intermediate-floods frequency and *STORMCLIMM* estimates over a relatively homogeneous and well-known period between 1910 and 1980.

Figure 3a illustrates the scatterplot of cumulative frequencies, with only little discrepancies between *STORMCLIMM* estimates and decadal intermediate-floods frequency. The lag-plot in Fig. 3b exhibits a linear pattern, indicating that the data are strongly nonrandom and with a serial correlation between the two cumulative series. The lag-plot also shows that cumulative series are free from outliers. Figure 3c shows, instead, that biases in the predicted intermediate floods tend to be associated with extreme values only.

3.2 Multidecadal flood-frequency and stormy climate evolution

Figure 4a represents the multiscale stormy climate data simulated for the whole period 1500–2010 (black curve). Comparisons between hydroclimatological forcing and MUDIF mean frequency (blue line) suggest that some coevolution had in fact occurred.

First, notable differences between the periods before and after the eighteenth century occur, with some particular contrasts in each of time series. The assimilation of multiscale stormy climate and MUDIF peaks in the RRB illustrates how important were the oscillations of large-scale rainstorms over the LIA, compared to the quietest climatic period 1850–1950. Such a minor climatic large-scale rainstorm situations (floods of low

Fig. 3 Evaluation of *STORMCLIMM* (Eq. 1). **a** Scatterplot of cumulative decadal data (CDD) between intermediate-floods and *STORMCLIMM* estimates (grey cross-points), with performed fitted line (in black bold) for the RRB from 1910 to 1980, **b** and **c** illustrate lagged-plot and QQ-plot of CDD-data, respectively

frequency) is supposed to be the first cause of the reduction in runoff, with impacts on the mass of sediment load in the RRB during this period (Arnaud-Fassetta 2003).

Grey area in Fig. 4a shows the Maunder Minimum (MM) as the climatic period with intermediate floods-dominated regime, although this was not completely corroborated by the estimated peak. These periods alternated with low flood frequencies (1590–1644 and 1690–1750), well captured in the simulation by *STORMCLIMM*. These last intervals correspond to a drought-dominated regime and a reduction in coastline progradation (Arnaud-Fassetta and Provansal 1999). Subsequently, a longer period (1750–1830) has been dominated by rainstorms and intermediate floods, though with minor intensity than in the MM. Since the end of the LIA (1850), the lower Rhone catchment has been subject to intermediate floods of smaller spatial extent (1886, 1897, 1910, 1935, 1951, 1955, 1993, 1994), and smaller fluctuations. However, after the 1980s, storm erosivity and related hydrological processes show a gradual rising and a shift to few large mixed floods with frequent and sudden pulses of storm water associated with more erratical flash and intermediate floods. These natural events have mainly driven the hydro-geomorphological processes that shaped RRB landscapes and vegetation, but the time patterns have been sometimes altered by human activity (shown by coloured boundaries above the graph of Fig. 4a).

Human-induced modifications of the vegetation cover in river basins may indeed cause strong geomorphic responses by disturbing sediment supply, transport and deposition regimes (Liébault et al. 2005). Throughout the time, different anthropogenic practices and landscape shaping succeeded. At its most general, deforestation is known to increase floods downstream by increasing runoff and increasing erosion and thereby sedimentation in river channels, thus reducing their ability to hold flood waters (Wasson 2008). In Europe and notably in France, the hold of the kings and nobility over the forests had weakened considerably by the sixteenth century, after which the emphasis on the use of the forests switched from hunting to the provision of wood. This marked the start of a period of pressure on the forests, which was most intense in the seventeenth and eighteenth centuries (Sands 2005).

The forest area decreased in France from about 35 % at the beginning of the sixteenth century to about 25 % by the middle of the seventeenth century (Ball 2001). In the second part of the seventeenth and the beginning of the eighteenth centuries, channel infilling, raising of river banks, appearance of crevasses and secondary channels, and accelerated delta progradation characterized a rapid change in fluvial environments of the RRB as driven by the sustained peak in MUDIF (grey time domain in Fig. 4a).

Fig. 4 **a** *STORMCLIMM* with high-pass filter (Eq. 1) output (black curve) and MUDIF cumulative mean frequency (blue line) over the period 1500–2010, with superimposed land-use change evolution (coloured band from green to grey) in the RRB, as rearranged from Pichard (1995), Miramont and Guilbert (1997) and Arnaud-Fassetta (2003); scales of rainstorm and climatic periods are also shown with marked the Maunder Minimum (1645–1715). **b** Monthly convective rain-flux component of storm erosivity (grey dots) evolving over the warming period 1980–2010, with overimposed 7th-order spline function. (Color figure online)

In accordance with Starkel (2002), high frequency of extreme rain events and fluvial activity coincides with the years of declined solar activity during the years of the Maunder Minimum (MM). This is the period roughly from 1645 to 1715 when sunspots became exceedingly rare, as noted by solar observers of the time (e.g. Vaquero et al. 2002). Meandering was particularly unstable, involving the multiplication of islands and crevasses and division of the riverbed along the axis of meander and, in 1712, the avulsion of the river displaced it to its present-day location (Arnaud-Fassetta and Provansal 1999).

Following the 1762–1776 famine in France, tax concessions were given to farmers to encourage them to clear even more forests for agriculture (Sands 2005). Widely open

landscape and intensive farming were characterized by cereal cultivation and the spread of walnut cultivation but, from the eighteenth century, the farming practices decreased and were substituted by grazing until nowadays (Doyen et al. 2011). Surell (1841) recognized that deforestation of the southern French Alps during the eighteenth century had increased erosion and overloading of headwater streams with sediments, and suggested that floods downstream may have worsened as a result. This is in correspondence with the more stable and moderate phase of MUDIF, during the century 1760–1860, despite this trend was not always shared by the hydroclimatological forcing (marked oscillation in *STORMCLIMM* in Fig. 4a).

However, whether cold and wet periods have facilitated intense torrential erosions, climatic degradation could also have had indirect consequences through vegetation cover modifications (Lang et al. 2003). In this way, fluvial responses may be dominated by the climatic shift in such circumstances, and climate change may also induce land-use changes, by making agriculture either possible or impossible. Evidence suggests that the interactions of land-use and climatic changes may involve considerable complexity in terms of their combined impacts on the response of fluvial systems. If people change land uses approximately in phase with climatic changes, then the fluvial response will be a result of both. In some cases, the two appear to operate essentially and independently, whereas in others they are closely linked and the impact of land-use change may only be fully apparent when coupled with climate (Wasson 1996).

Over the period spanning from about 1500 to 1800, it can be accepted that the generation of intermediate floods in the RRB was intimately connected with multidecadal climate variability, and secondarily with land-use change. This situation, in which flooding seemed to be accepted as a tribute paid to nature continued until the nineteenth century. At that point, there was a change of attitude because the technological innovations of the time made it possible to build important structures designed to contain the river. Still between about 1800 and 1850, in the Clarée Valley (Clarée is a tributary to the Durance, which flows into the Rhone near Avignon), torrents on alluvial fans were up to four times wider by comparison with the twenty-first century (Garitte 2006). After the great floods of 1840 and 1856, as well as the considerable extension of urban areas, major efforts to protect the population were undertaken: those living along the river were partially protected, quays and barriers were built and the street levels raised around them (through <http://www.fleuverhone.com>).

Reforestation is documented from about 1865 in the southern Prealps (de Gayffier 1877; Liébault et al. 2005). The reforestation in the Roubion catchment (Roubion is a left bank tributary of the middle Rhone) is correlated with a decrease of peak flows; channels narrowed and deepened as sediment supply was reduced as riparian forest regrew, and incised river reaches developed stable gravel pavements (Liébault and Piégay 2001). Between 1850 and 1950, human artefacts appear to be important, such as fluvial flood defence embankment and reforestation (Roux et al. 1989). When there is a strong, rapid rise in the water level, certain flood protection dams direct the water into agricultural or peri-urban areas in order to avoid flooding in more highly populated sectors. However, the flood protection dams are ineffective when there is major flooding because the dykes separating the river from its natural overflow areas amplify the impact of floods in the surrounding territories.

The severe floodings occurred between 1993 and 2003 in the Rhone catchments of Switzerland and France caused loss of life (2003) and billions of euros in damages (Bravard 2006; Arnaud-Fassetta et al. 2009). In the Gardon gorge (Gardon River ends into the Rhone at Comps, 43.85 latitude North, 4.61 longitude East), for instance, an extreme

flood on the 8–9th of September 2002 claimed the lives of 24 persons and resulted in an economic damage evaluated at 1.2 billion euros (Delrieu et al. 2005). These examples testify that, in recent times, the interrelationship between land-use and climate changes has newly become strong in the RRB, but with damaging hydrological events largely associated with a more erratic spatial and temporal distribution of extreme rainfalls, in the form of local-scale pulsing rainstorms that also affect other Mediterranean areas (Diodato and Bellocchi 2010; Grauso et al. 2010).

This can increase land degradation and human vulnerability (arrow in Fig. 4a) due to both unexpectedly erratical intermediate floods and drastic changes of land use, involving substantial monetary and nonmonetary impacts (Wetter et al. 2011). Indeed, yet minimizing the flood hazard, channelling may lead to an increase in risks because rarer floodings have become more destructive to properties and assets (Arnaud-Fassetta 2003). This most recent evolution shows a noticeable increase of flood occurrence in conjunction with an increase of flash-flood events. This assumption was corroborated, since the 1990s, by increased peaks of convective rain fluxes across the RRB (Fig. 4b).

The rise in extreme rainfall events was not homogeneous over all the months and on the whole of RRB. As shown in Fig. 5, a shift of rainfall anomalies in July (graph a) and October (graph c) is observed towards the northern part of RRB over the decade 2000–2009 by comparing it with 1950–1999.

Peaks of 30–50 mm in October were mainly found north of Lyon and where the watershed borders Switzerland. September shows a peculiar and positive anomaly pattern in the area near Marseille (graph b). Similar to the results reported for the central Mediterranean area (Diodato and Bellocchi 2010), extreme rainstorm events tend to become more intense and frequent around coastlines. In Barcelona (east coast of Spain), for instance, there were the flash floods of 21 September 1995 (high rainfall of 80 mm in half an hour) and the 31 July 2002 (115 mm of rainfall being recorded in less than 4 h) (Barrera et al. 2005).

Fig. 5 Rainfall spatial patterns anomalies (2000–2009 minus 1950–1999) across the RRB for July, September and October. Maps were arranged from Climate Explorer (van Oldenborgh et al. 2009); 2000–2009 data were extracted from TRMM platform of NASA (<http://wdc.dlr.de/sensors/tmi>); 1950–1999 data are from the Global Precipitation Climatology Centre (<http://www.dwd.de>) observational dataset

4 Summary and conclusions

Parsimonious models are appealing for predicting catchment scale hydroclimatological variables when high-resolution precipitation data are not available. The present study offers an application of a multiscale model of annual rainstorms based on annual summer rainfalls (in the high-pass filter option) and bidecadal inputs of seasonal precipitation (*STORMCLIMM*), used to assess the distribution of intermediate floods in the RRB. Rainstorm magnitude is controlled by the extremes of precipitation and exhibits variability in a variety of time scales. The predictability of long-term rainstorms may depend on the nature of annual variability of precipitations, which in turn exhibit important decadal-to-interdecadal variability. Modulation of annual variability by the bidecadal variability of season rainfall inputs, as in the *STORMCLIMM*, may thus influence predictability of annual rainstorms. The study shows that a satisfactory model performance can be obtained from few reasonable and physically sound climate assumptions. The model structure and parameterization may need to be refined in future and conclusions cannot be generalized without additional research. In spite of this, the results suggest that a small number of inputs and coefficients are sufficient to represent the distribution of intermediate floods with enough detail for a medium-size catchment. This lays the foundation for future applications in other river catchments and for the reconstruction of historical intermediate floods from seasonal inputs. However, the connection between storm events and intermediate-flood frequency is more difficult to judge where land-use changes are concerned. Evolution of hydroclimatology in the RRB was thus assessed by combining flood-causing storms and land-use changes. The evolution of intermediate-flood occurrence in the RRB, from the sixteenth century down to the present day, shows the existence of climatic oscillations during the Maunder Minimum, in the late part of the Little Ice Age, and in the most recent decades. The importance of climatic fluctuations on the fluvial system evolution is clearly disclosed, though intimately connected to land-use changes. In particular, the increased trend observed in the number of intermediate floods documented over the twentieth century can mainly be attributed to evolution of the perception threshold and changes in vulnerability and urban conditions from the middle of the nineteenth century. Taking the RRB as an exemplar of Euro-Mediterranean medium-sized basins, we can assume (but this needs to be confirmed) that the frequency of intermediate floods is in a phase of increasing, due both to some natural conditions (increasing in rain erosivity due probably to climate changes) and to human influence (changes in agricultural activities and urban land uses).

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References

- AA.VV. (1983) Report on a Workshop on Mitigation Strategies for Communities Prone to Multiple Natural Hazards. Advisory Board on the Built Environment, Commission on Engineering Technical Systems and National Research Council, July 6–8, Snowmass, Colorado. National Academic Press, Washington, DC, pp 1–22
- Anquetin C, Ducrocq V, Braud I, Creutin J-D (2009) Hydrometeorological modelling for flash flood areas: the case of the 2002 Gard event in France. *J Flood Risk Manage* 2:101–110

- Antoine J-M, Desailly B, Gazelle F (2001) Les crues meurtrières, du Roussillon aux Cévennes. *Ann Géogr* 622:597–623 (in French)
- Arnaud-Fassetta G (2003) River channel changes in the Rhone Delta (France) since the end of the Little Ice Age: geomorphological adjustment to hydroclimatic change and natural resource management. *Catena* 51:141–172
- Arnaud-Fassetta G, Provansal M (1999) High frequency variations of water flux and sediment discharge during the Little Ice Age (1586–1725 AD) in the Rhône Delta (Mediterranean France). Relationship to the catchment basin. *Hydrobiologia* 410:241–250
- Arnaud-Fassetta G, Astrade L, Bardou E, Corbonnois J, Delahaye D, Fort M, Gautier E, Jacob N, Peiry J-L, Piégay H, Penven M-J (2009) Fluvial geomorphology and flood-risk management. *Géomorphol Relief Process Environ* 2:109–128
- Ball JB (2001) Global forest resources: history and dynamics. In: Evans J (ed) *The forests handbook*, vol 1. Blackwell Science, Oxford, pp 3–22
- Barrera A, Barriendos M, Llasat MC (2005) Extreme flash floods in Barcelona County. *Adv Geosci* 2:1–6
- Barrera A, Llasat MC, Barriendos M (2006) Estimation of extreme flash flood evolution in Barcelona County from 1351 to 2005. *Nat Hazards Earth Syst Sci* 6:505–518
- Bianciotto L (2005) Les crues du Gardon sur la commune d’Anduze: approche historique et enjeux. Thesis of Master in: UFR Sciences humaines et sciences de l’environnement, Master sciences de l’homme, des territoires et de la société, Université Paul-Valéry Montpellier III, Dynamiques spatiales, gestion des territoires, développement (in French)
- Bobee B, Rasmussen PF (1995) Recent advances in flood frequency analysis. *Rev Geophys* 33:1111–1116
- Boni G, Parodi A, Siccaldi F (2008) A new parsimonious methodology of mapping the spatial variability of annual maximum rainfall in mountainous environments. *J Hydrometeorol* 9:492–506
- Braud I, Roux H, Anquetin S, Maubourguet MM, Manus C, Viallet P, Dartus D (2010) The use of distributed hydrological models for the Gard 2002 flash-flood event understanding. Part II: analysis of the associated hydrological processes. *J Hydrol* 394:134–147
- Bravard J-P (2006) Impacts of climate change on the management of upland waters: the Rhone river case. Fifth Biennial Rosenberg International Forum on Water Policy. Banff
- Clarke ML, Rendell HM (2005) Climate, extreme events and land degradation. In: Kirch W, Menne B, Bertolini R (eds) *Extreme weather events and public health responses*. Springer, Berlin, pp 136–152
- D’Odorico P, Yoo J, Over TM (2001) An assessment of ENSO-induced patterns of rainfall erosivity in the Southwestern United States. *J Climate* 14:4230–4242
- De Gayffier E (1877) Reboisement et gazonnement des montagnes. Photographies de travaux de consolidation et de reboisement. Document préparé pour l’exposition universelle de 1878.66 prises de vues, 7 vues téléiconographiques (in French)
- De Lima MIP, de Lima JLM (2009) Investigating the multifractality of point precipitation in the Madeira archipelago. *Nonlinear Process Geophys* 16:299–311
- Delrieu G, Ducrocq V, Gaume E, Nicol J, Payrastra O, Yates E, Kirstetter P-E, Andrieu H, Ayral P-A, Bouvier C, Creutin J-D, Livet M, Anquetin S, Lang M, Neppel L, Obled C, Parent-du-Chatelet J, Saulnier GM, Walpersdorf A, Wobrock W (2005) The catastrophic flash-flood event of 8–9 September 2002 in the Gard region, France: a first case study for the Cévennes-Vivarais Mediterranean Hydro-meteorological Observatory. *J Hydrometeorol* 6:34–52
- Diodato N (2010) Combining satellite and geospatial technologies for exploring rainstorm hazard over Mediterranean Central Area. In: Diodato N (ed) *Satellite communications*. Sciyo, Rijeka, pp 153–162
- Diodato N, Bellocchi G (2010) Storminess and environmental changes in the Mediterranean central area. *Earth Interact* 14:1–16
- Diodato N, Bellocchi G (2012) Decadal modelling of rainfall-runoff erosivity in the Euro-Mediterranean region using extreme precipitation data. *Glob Planet Change* 86–87:79–91
- Diodato N, Bellocchi G, Romano N, Chirico GB (2011) How the aggressiveness of rainfalls in the Mediterranean lands is enhanced by climate change. *Clim Change* 108:591–599
- Diodato N, Petrucci O, Bellocchi G (2012) Scale-invariant rainstorm hazard modelling for slopeland warning. *Meteorol Appl* 19:279–288
- Doyen E, Vannière B, Millet L, Berger J-F, Arnaud F (2011) Vegetation dynamic and land-use history through the Holocene in Eastern France. INQUA 2011 congress: Quaternary Science, Bern
- Dunne T, Black RD (1970) An experimental investigation of runoff production in permeable soils. *Water Resour Res* 6:478–490
- Espósito E, Porfido S, Violante C, Molisso F, Sacchi M, Santoro G, Spiga E (2011) Flood risk estimation through document sources analysis: the case of the Amalfi rocky coast. DTA, DTA/06 (<http://eprints.bice.rm.cnr.it/4020>)

- EXCIMAP (2007) Handbook on good practices for flood mapping in Europe. EXCIMAP (a European Exchange Circle on Flood Mapping). Endorsed by Water Directors (http://ec.europa.eu/environment/water/flood_risk/flood_atlas)
- Foster GR, Meyer LD, Onstad CA (1977) A runoff erosivity factor and variable slope length exponents for soil loss estimates. *Trans ASAE* 20:683–687
- Gallart F, Llorens P, Latron J, Regüés D (2002) Hydrological processes and their seasonal controls in a small Mediterranean mountain catchment in the Pyrenees. *Hydrol Earth Syst Sci Discuss* 6:527–537
- García-Ruiz JM, Arnáez J, Beguería S, Seeger M, Martí-Bono C, Regüés D, Lana-Renault N, White S (2005) Runoff generation in an intensively disturbed, abandoned farmland catchment, Central Spanish Pyrenees. *Catena* 59:79–92
- Garitte G (2006) Les torrents de la vallée de la Clarée. Evolution contemporaine, dynamique actuelle et analyse géographique des risques associés. PhD thesis, Université des Sciences et Technologies de Lille (in French)
- Gaume E, Bain V, Bernardara P, Newinger O, Barbuc M, Bateman A, Blaškovičová L, Blöschl G, Borga M, Dumitrescu A, Daliakopoulos I, Garcia J, Irimescu A, Kohnova S, Koutroulis A, Marchi L, Matreata S, Medina V, Preciso E, Sempere-Torres D, Stancalie G, Szolgay J, Tsanis I, Velasco D, Viglione A (2009) A compilation of data on European flash floods. *J Hydrol* 367:70–78
- Glaser R, Riemann D, Schönbein J, Barriendos M, Brázdil R, Bertolin C, Camuffo D, Deutsch M, Dobrovolný P, van Engelen A, Enzi S, Halíčková M, Koenig SJ, Kotyza O, Limanówka D, Macková J, Sghedoni M, Martin B, Himmelsbach I (2010) The variability of European floods since AD 1500. *Clim Change* 101:235–256
- Gozzini B, Maracchi G, Mozzanti B, Menduni G, Meneguzzo F, Pasqui M, Volpini F (2007) Acquisition and analysis of historical series of hourly pluviometric data. In: 19th conference on climate variability and change, 87th AMS Annual meeting, San Antonio, TX
- Grauso S, Diodato N, Verrubbi V (2010) Calibrating a rainfall erosivity assessment model at regional scale in Mediterranean area. *Environ Earth Sci* 60:1597–1606
- Grove AT (2001) The “Little Ice Age” and its geomorphological consequences in Mediterranean Europe. *Clim Change* 48:121–136
- IFEN (2006) Le sol et le sous-sol. In: *L’environnement en France—édition 2006*. Institut Française l’Environnement, Orléans, pp 251–272 (in French)
- Lang M, Cœur D, Brochet S, Naudet R (2003) Information historique et ingénierie des risques naturels. L’Isère et le torrent du Manival. Cemagref Editions, série Gestion des milieux aquatiques, n° 18 (in French)
- Liébault F, Piégay H (2001) Assessment of channel changes due to long-term bedload supply decrease, Roubion River, France. *Geomorphology* 36:167–187
- Liébault F, Gomez B, Page M, Marden M, Peacock D, Richard D, Trotter C (2005) Land-use change, sediment production and channel response in upland regions. *River Res Appl* 21:739–756
- Llasat MC (2001) An objective classification of rainfall events on the basis of their convective features: application to rainfall intensity in the Northeast of Spain. *Int J Climatol* 21:1385–1400
- Matos Silva M (2011) El modelo Barcelona de espacio público y diseño urbano: public space and flood management/dipòsits d’aigües pluvials. Master Oficial en Disseny Urbà: Art, Ciutat, Societat, University of Barcelona, Spain
- MEDAD (2006) Les collectivités locales et le ruissellement pluvial. Ministère de l’Ecologie, du Développement et de l’Aménagement Durable, Direction de la Prévention des pollutions et des risques—Sous-direction de la Prévention des risques majeurs 20, avenue de Ségur, 75302 Paris 07 SP (<http://www.developpement-durable.gouv.fr>, <http://www.prim.net>)
- MEDAD (2006) Plan de prévention des risques naturels inondation, Bassin versant du Lez. Rapport de présentation du maître d’œuvre. Ministère de l’Ecologie, du Développement et de l’Aménagement Durable, Direction Départementale de l’Équipement, p 35 (in French)
- Merz R, Piock-Ellena U, Blöschl G, Gutknecht D (1999) Seasonality of flood processes in Austria. In: Gottschalk L, Olivry JC, Reed D, Rosbjerg D (eds) *Hydrological extremes: understanding, predicting, mitigating*. IAHS Publ. 255, pp 273–278
- Miramont C, Guilbert X (1997) Variations historiques de la fréquence des crues et évolution de la morphogénèse fluviale en moyenne Durance (France du Sud-Est). *Géomorphologie: relief, processus, environnement* 4:325–338 (in French)
- Miramont C, Jorda M, Pichard G (1998) Évolution historique de la morphogénèse et de la dynamique fluviale d’une rivière Méditerranéenne: l’exemple de la moyenne Durance (France du sud-est). *Géogr Phys Quat* 52:1–13 (in French)
- Parajka J, Kohnová S, Bálint G, Barbuc M, Borga M, Claps P, Cheval S, Gaume E, Hlavčová K, Merz R, Pfaundler M, Stancalie G, Szolgay J, Blöschl G (2010) Seasonal characteristics of flood regimes across the Alpine-Carpathian range. *J Hydrol* 394:78–89

- Pauling A, Luterbacher J, Casty C, Wanner H (2006) Five hundred years of gridded high-resolution precipitation reconstructions over Europe and the connection to large-scale circulation. *Clim Dynam* 26:387–405
- Petrucci O, Polemio M (2003) The use of historical data for the characterisation of multiple damaging hydrogeological events. *Nat Hazards Earth Syst Sci* 3:17–30
- Petrucci O, Polemio M (2009) The role of meteorological and climatic conditions in the occurrence of damaging hydro-geologic events in Southern Italy. *Nat Hazards Earth Syst Sci* 9:105–118
- Pichard G (1995) Les crues sur le bas Rhône de 1500 à nos jours. Pour une histoire hydro-climatique. Méditerranée 3–4:105–116 (in French)
- PLANRIN (2006) Plan de prevention des risques naturels inondation. Bassin versant du Lez. Ministère de l'Ecologie et du Développement Durable, Direction Départementale de l'Équipement, Vaucluse-Drôme (in French)
- Radziejewski M (2011) About trend detection in river floods. In: Kropp JP, Schellnhuber HJ (eds) *In extremis: disruptive events and trends in climate and hydrology*. Springer-Verlag, Berlin, pp 145–165
- Romero R, Guijarro JA, Ramis C, Alonso S (1998) A 30-year (1964–1993) daily rainfall data base for the Spanish Mediterranean regions: first exploratory study. *Int J Climatol* 18:541–560
- Roux AL, Bravard JP, Amoros C, Pautou G (1989) Ecological changes of the French upper Rhone River since 1750. In: Petts GE, Mçller H, Roux AL (eds) *Historical change of large alluvial rivers: Western Europe*. Wiley, Chichester, pp 323–350
- Ruin I, Creutin J-D, Anquetin S, Lutoff C (2008) Human exposure to flash-floods—relation between flood parameters and human vulnerability during a storm of September 2002 in Southern France. *J Hydrol* 361:199–213
- Sands R (2005) *Forestry in a global context*. CABI, Wallingford
- Schad I, Schmitter P, Saint-Macary C, Neef A, Lamers M, Nguyen L, Hilger T, Hoffmann V (2011) Why do people not learn from flood disasters? Evidence from Vietnam's northwestern mountains. *Nat Hazards*. doi:10.1007/s11069-011-9992-4
- Seeger M, Errea MP, Beguería S, Arnáez J, Martí C, García-Ruiz JM (2004) Catchment soil moisture and rainfall characteristics as determinant factors for discharge/suspended sediment hysteretic loops in a small headwater catchment in the Spanish Pyrenees. *J Hydrol* 288:299–311
- Starkel L (2002) Change in the frequency of extreme events as the indicator of climatic change in the Holocene (in fluvial systems). *Quat Int* 91:25–32
- Stephen J, DeGaetano AT (2008) A statistical comparison of the properties of flash flooding and nonflooding precipitation events in portions of New York and Pennsylvania. *Weather Forecast* 23:114–130
- Surell A (1841) *Étude sur les torrents des Hautes Alpes*. Dunod, Paris (in French)
- Van Oldenborgh GJ, Drijfhout S, van Ulden A, Haarsma R, Sterl A, Severijns C, Hazeleger W, Dijkstra H (2009) Western Europe is warming much faster than expected. *Clim Past* 5:1–12
- Vaquero JM, Sánchez-Bajo F, Gallego MC (2002) A measure of the solar rotation during the Maunder minimum. *Sol Phys* 207:219–222
- Verstraeten G, Poesen J, Demarée G, Salles C (2006) Long-term (105 years) variability in rain erosivity as derived from 10-min rainfall depth data for Ukkel (Brussels, Belgium): implications for assessing soil erosion rates. *J Geophys Res* 11:D22109. doi:10.1029/2006JD007169
- Wasson RJ (1996) Land use and climate impacts on fluvial systems during the period of agriculture. PAGES workshop report, series 96-2
- Wasson RJ (2008) Upland deforestation, erosion, and downstream impacts. In: Sanchez IB, Alonso CL (eds) *Deforestation research progress*. Nova Science, New York, pp 51–65
- Wessa P (2011) Free Statistics Software, Office for Research Development and Education, version 1.1.23-r7 (<http://www.wessa.net>)
- Wetter O, Pfister C, Weingartner R, Luterbacher J, Reist T, Trösch J (2011) The largest floods in the High Rhine basin since 1268 assessed from documentary and instrumental evidence. *Hydrol Sci J* 56:733–758
- Wischmeier W, Smith D (1958) Rainfall energy and its relationship to soil loss. *Trans Am Geophys Union* 39:131–137