ANALYSIS OF THE SPATIAL STRUCTURE OF THE 4 OCTOBER 2021 EXTREME RAINFALL EVENT IN LIGURIA AND EVALUATION OF ITS IMPACT ON THE ESTIMATION OF ANNUAL MAXIMA

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KEY POINTS

- *The paper shows the analysis of the spatial scale of rainfall produced by a back-building Mesoscale Convective System.*
- *The analysis is conducted combining rain gauge and radar observations.*
- *The results show that the spatial scale is of the same order of (or lower than) the density of rain gauge networks.*
- *This may significantly impact the estimation of the actual rainfall maxima and their return period.*

1 INTRODUCTION

This work analyses the extreme rainfall event that occurred on 4 October 2021 in Liguria. This event represents a significant example of Mediterranean Back-building MCS precipitation events (*Nuissier et al.*, 2008; *Fiori et al.*, 2014), that are usually characterized by a very small spatial extent. The 4 October event has registered the highest values of cumulative rainfall ever recorded in Liguria for the 3, 6, 12 hours durations. Therefore, this event can be considered as an example of Extraordinary Extreme Event (EEE) (*Pelosi et al.*, 2020) similar to other historically observed events, which produced the annual maximums of precipitation for short durations, commonly used for the probabilistic analysis of precipitation and flood hazard (e.g., *Skahill & Kanney*, 2019).

The event analysis has been performed using multi-sensor observations provided by the Liguria region rain gauge network and the C-band weather radars of the Italian Radar Network. The aim of this analysis has been the identification of the characteristic spatial scale of the precipitation structure caused by the back-building MCS, represented by the cross-sectional dimension of the peak structures, and the comparison of this dimension with the average rain gauge density.

Rain gauge data are used to obtain statistics of extreme rainfall, usually expressed by rainfall depth-duration-frequency (DDF) curves (*Burlando & Rosso*, 1996; *Koutsoyiannis et al.*, 1998). This statistical approach relies on the assumption that the maxima observed by the stations are matching with the local maxima of the actual event. The lower is the average rain gauge density compared to the characteristic spatial scale of the MCS precipitation event, the less valid is the aforementioned hypothesis. Nonetheless, the effects of the discrepancy between the coarse spatial spacing of point rainfall observations and the typical size of EEEs spatial structures at a daily scale has been already observed by *Pelosi et al.* (2020), highlighting a dramatic underestimation of the rainfall depth at very high return periods if traditional statistical methods are applied.

The spatial analysis of the 4 October event underlines that the discrepancy between the characteristic spatial scale of the MCS precipitation events and the average rain gauge density can be extremely significant.

2 THE 4TH OF OCTOBER 2021 RAINFALL EVENT

Between Sunday 3 and Tuesday 5 October 2021, North-West Italy has been invested by the passage of an intense frontal system, responsible for severe rainfalls and consequent riverine flooding and landslides. Starting from 3 October, the synoptic analysis shows that a deep Atlantic trough extended from north Atlantic to the Iberian Peninsula, bringing an intense moist current from southwest towards north-western Italy. At the same time, a vorticity advection over Spain was observed, linked to the displacement of a low pressure wave from Portugal to the Balearic Islands. Such vorticity advection over the Mediterranean contributed to increasing the energy available for convection and, therefore, to increase the atmospheric instability over the Tyrrhenian regions, especially the Ligurian Gulf. During the early hours of 4 October, the warm sea environment, fed by south-west winds associated with the Atlantic low pressure and pronounced wind shear, paved the way for a V-shape back-building MCS generation (affecting the Piedmont-Ligurian watershed with intense convective and localized rainfall. The convective structure was characterized by an intense convergence line over the Ligurian sea spanning between Genoa and Savona city. This configuration (convergency line and high wind shear values), associated to Ligurian steep orography, stuck the back-building MCS over the same area for many hours (see *ARPA Piemonte* (2021)) for details about synoptic and event description).

The most relevant phenomena affected the Apennine reliefs close to the Ligurian Sea on Monday 4 October. The back-building Mesoscale Convective System stood between the provinces of Savona (SV) and Genoa (GE), in the Liguria region, and the province of Alessandria, in the Piedmont region, causing the overcoming of the maximum cumulative rainfall over several time windows ever recorded in the region. Table 1 reports the recorded maxima and the corresponding locations.

Duration [h]	Cumulated rainfall [mm]	Rain gauge station	Province
1	178.2	Urbe Vara Superiore	Savona
3	**377.8**	Urbe Vara Superiore	Savona
6	**496**	Montenotte Inferiore	Savona
12	**740.6**	Rossiglione	Genoa
24	883.8	Rossiglione	Genoa

Table 1. Maximum accumulated rainfall values for different durations (1, 3, 6, 12, 24 hours) recorded on 4 October 2021 in Liguria and the corresponding rain gauge station. The values in bold correspond to the regional records. Data provided by Regione Liguria, ARPA.

The 4 October event presents similar characteristics to other historical events that struck the Liguria region producing annual rainfall maxima (e.g., *Fiori et al.*, 2014; *Parodi et al.*, 2017; *Lagasio et al.*, 2017).

3 SPATIAL ANALYSIS OF THE PRECIPITATION EVENT

The aim of this analysis is the identification of the characteristic spatial scale of the precipitation structure of the 4 October event, represented by the shorter cross-sectional dimension of the peak structures, and its comparison with the average rain gauge density.

To quantitatively evaluate the spatial scale of the peak precipitation structures caused by back-building MCSs during the event, the SRI (Surface Rainfall Intensity) product by the Italian Radar Network (*Vulpiani et al.*, 2008) has been used. This product provides an estimation of precipitation intensity near the ground with a temporal resolution of 5 minutes. SRI intensities are pre-processed extracting the pixel with the maximum cumulated rainfall over different durations (1, 3, 6, 12, 24 hours). SRI intensities in the whole analysed region for the same period when the maximum has been observed represent then the peak structure of the rainfall field. The peak structures for all durations considered have been then non-dimensionalized using the corresponding maximum value.

The non-dimensionalization was adopted as the purpose of the analysis is to compare the distance at which the cumulative of the event is significantly reduced and the average distance between the rain gauges and not to compare the absolute values observed by radar and rain gauges.

The average distance between two adjacent rain-gauging stations has been calculated as the squared root of the rain-gauging stations' density inside the study area and has been estimated equal to around 6 kilometres.

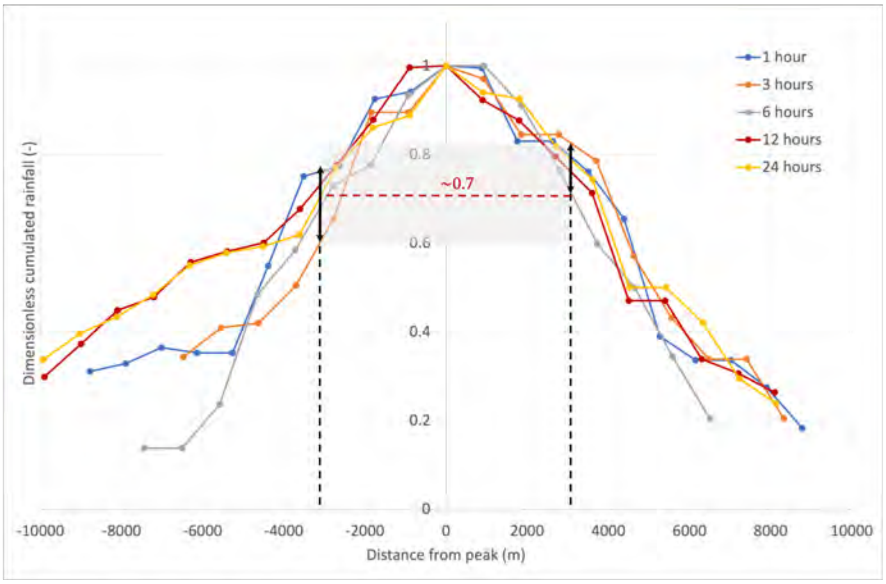

Figure 1. Cross-sections of non-dimensional rainfall fields for cumulated rain for 1 to 24 hours. It is shown that at distances equal to half of the average rain gauge network (3 km) the accumulated rainfall can be about 70% of the peak, for all durations considered.

In Figure 1, the shorter cross-sectional shape of the non-dimensional rainfall fields for the durations considered is shown. It can be seen that at distances corresponding to about the half cross sectional dimension, average relative accumulated rainfall is around 70% of the peak. As a consequence, for this kind of events, the probability of having a rain gauge located below the rainfall peak can be significantly reduced, with a consequent reduction in the probability of recording the real rainfall maximum for a given event.

This is shown also in Figure 2. Here the non-dimensional peak structure for the accumulation period of 12 hours is shown, with the position of the Rossiglione (GE) gauging station, which recorded the maximum for this duration (see Table 1). Compared to the SRI-derived non-dimensional peak structure, the maximum recorded at Rossiglione seems to be 20% lower and located around 2.5 km far from the peak. The radar measure can be potentially affected by a spatial bias and the rainfall peak cannot be properly located at the ground; nonetheless, the radar can be considered reliable in the identification of the size of the structure and therefore in the evaluation of the relative increase or decrease of rainfall intensities from one pixel to another. Indeed, the analysis of the cumulated rainfall reported in Figure 2 well underlines how extreme rainfall events like the one analysed can easily produce an underestimation of the peak for rain gauge densities like those of the study region.

4 DISCUSSION AND CONCLUSIONS

Statistics of extreme rainfall are crucial for design purposes in water management (e.g. construction of sewerage systems, determination of the required discharge capacity of channels), flood risk estimation, and consequently for the design and management of structural flood protection measures (*Koutsoyiannis*, 2007; *Overeem et al.*, 2008). Therefore, reliable calculation of probabilities of extreme rainfall is of concern.

Rain gauge data are used to obtain statistics of extreme rainfall usually quantified by DDF curves. This statistical approach relies on the assumption that the maxima observed by the stations are matching with the local maxima of the actual event. The density of rain gauge stations in a given region directly influences the representativeness of the measures as compared with the actual precipitation in the region (*WMO*, 2008) and therefore the reliability of the derived statistics. According to the guidelines reported by *WMO* (2008) this density can vary from one station every 100 km^2 for the lowland areas up to one station every 50 km^2 for the hilly and mountainous regions. The area hit by the 4 October 2021 event is then theoretically compliant with WMO guidelines, since the spatial density of the rain gauge network is lower than one station every 40 km^2.

According to our analysis, these suggested rain-gauging networks' spatial densities however appear not adequate to catch rainfall maxima, considering typical Mediterranean extreme events producing annual rainfall maxima for durations up to 24 hours. Indeed, as reported in Section 3, the size of the cross-sectional dimension of the peak rainfall structures for that event is of the same order of magnitude as the rain gauge spatial density.

This highlights the importance of adapting the concept of support area as introduced by *Pelosi et al.* (2020) to sub-daily durations, using the potential offered by satellite observations.

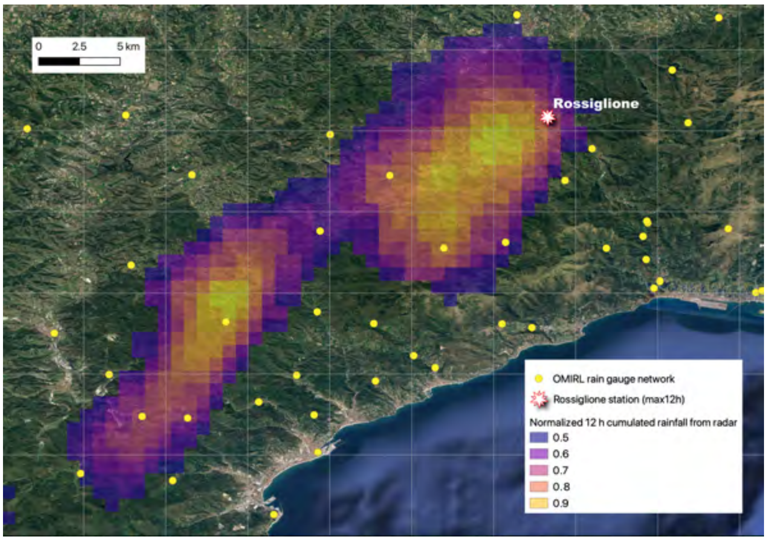

Figure 2. Maximum normalized cumulated rainfall over 12 hours observed on 4 October 2021, Rossiglione rain gauge station (which has observed the maximum of the event over the 12 hours), and the OMIRL rain gauge network.

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