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Weather Radar and raingauge data fusion for rainfall estimation: The Livorno 2017 case

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Abstract

A severe weather event mainly interesting the coastal area of the Livorno and Pisa provinces occurred during the night between the 9th and 10th of September 2017. The event was rather limited in terms both of size of the involved area and of temporal duration, but the exceptional amount of rainfall caused the flooding of three torrents and landslides in the urban area of Livorno, and the loss of life of 8 people and extensive damages undergone by the entire urban area. Both the regional raingauge network and the operational weather radars correctly detected such a heavy rainfall event. The quantities measured by the rain gauges recorded peak values above 230 mm in three hours, but unfortunately the distance between the measuring points did not allow the event to be perfectly reconstructed. On the contrary, the radar and satellite systems were able to follow the event development and highlighted the most intense areas, although with little accuracy for what concerns the quantitative values.

This work presents a data fusion technique for the real time estimation of the time-continuous 2D cumulative rainfall fields, based on radar and raingauge data. The technique has been applied to the dataset relative to the Livorno event. The results show the benefits of this data fusion scheme in terms of better localization and monitoring of dangerous rainfall patterns, in a perspective of early warning detection.

1. Introduction

In [1] the authors proposed a procedure for merging weather radar and raingauges observations aimed at estimating the spatial distribution of the rainfall cumulated over an observation time interval *T*. The purpose of the method is to merge the positive features characterizing each of the two kinds of instruments available over an observed area, namely the high point accuracy of raingauge observations with the high space/time resolution of radar measurements. The selected observation time *T* can be the whole duration of a rainfall phenomenon or a fraction of it. The resulting estimation of the rainfall field is based on the processing of a data set composed by raingauge and radar reflectivity observations gathered during the same rainfall phenomenon. This ensures that the empirical relationship between reflectivity and rainfall is based on measurements relative to the precipitation event and is consequently adapted to the weather system.

The proposed method has been applied to a severe rainfall phenomenon occurred along the coastal area of Tuscany and mainly interesting the Pisa and Livorno provinces. The event developed in the night between the 9th and 10th of September 2017. Though the alert state for adverse meteorological condition was declared in the evening of the 9th for the whole following day, the effects were catastrophic, particularly in the urban area of Livorno. The flash flood of three torrents and landslides due to the huge amount of precipitation caused the interruption of roads, the destruction of bridges, the inundation of cellars and houses and the tragic death of 8 people. Multiple storm systems originated and developed between the sea and the coast from 20 UTC of 9th September to 6 UTC of 10th September, with three intense periods. The regional raingauge network detected all these three very intense peaks of precipitation, but probably the strongest rainfall area was not covered by any raingauge. This is partially confirmed by the available weather radars, both those belonging the national mosaic and those of the Tuscany regional network. Radar scans continuously monitored the weather sequence and provided continuous updates of the precipitation systems development. They were used during the meteorological vigilance by weather forecasters, but they did not prove to be reliable in terms of accuracy of the provided quantities. This work shows and comments on the results of the data fusion procedure proposed in [1] and applied to the Livorno 9th/10th September case study. In particular, we show how the procedure is able to mitigate the well known problems related to the spatial resolution of raingauges and to the scarce quantitative reliability of rainfall estimates obtained through direct radar data conversion [2]-[8]. As proposed in [9, 10], a decision flowchart can be introduced to optimally exploit the complementary information of lightning, radars, satellites and raingauges, by selecting the most suitable sensors and parameters during the monitoring process. In this framework, the proposed data fusion scheme could be beneficial for generating more reliable time sequences of 2D rainfall maps to be used for real time detection and localization of potentially dangerous rainfall phenomena in an integrated early warning system.

2. The 9-10 Sep. 2017 weather event

From a synoptic point of view, starting from the late afternoon of September 9th, an extensive pressure trough affected the western Mediterranean. This recalled an intense current flow from the south, mild and extremely humid, on all the Tyrrhenian sectors and on the eastern side of the Ligurian Sea. A remarkable increase of humidity and suspended water was present, potentially dangerous in terms of precipitation. In the succession of the event, some atmospheric instability conditions showed up due to a colder airflow, with the triggering of convective storms. These were locally persistent because of the slow evolution of the depression area and of the wind shear effects on the updraft/downdraft separation. Moreover, the high temperature of the sea surface amplified the intensity of the precipitation event. The areas most affected by very intense and stationary storms are the Pisa and Livorno provinces (in particular, the coastal areas and the immediate hinterland). Specifically, most of the rainfall over the Pisa area occurred between 23:00 and 2:00 UTC in the night, and between 2:00 and 5:00 UTC in Livorno. This testifies that the event propagated slowly from north to south-east.

3. The raingauge and radar data set

As shown in [9], the most widely used instruments for meteorological vigilance purposes are satellites, radars, and raingauges, jointly with the outputs of numerical weather prediction models. Although the models are fundamental during the weather forecasting phase, the alert management phase requires instrumental observations, as they allow the nowcasting of precipitation. The weather event of the selected case study could be very well identified through satellite data, but as this study is oriented to an improvement of Quantitative precipitation estimation (QPE), the analysis will focus on raingauge and radar observations for their higher spatial resolution.

3.1 Raingauge network

The Tuscany raingauge network consists of more than 600 point measurements providing near real time ground rainfall observations. The network instruments are Tipping Bucket Raingauges that are widely used due to their simplicity and reliability and limited installation and maintenance costs. During the rainfall event, the network registered a first peak from 19:45 to 20:45 UTC, with cumulative rainfall amount of more than 60 mm over the Pisa area. Later, an additional peak showed up over Pisa between 22:45 and 00:30 UTC. Finally, starting from 01:30 UTC, a new strong temporal impulse, the most violent, hit mainly the zone between the southern area of the city of Livorno and Rosignano. In these areas, cumulative rainfall values of more than 40 mm / 15 min, 120 mm / 1 hour and 230 mm / 3 hours were reached.

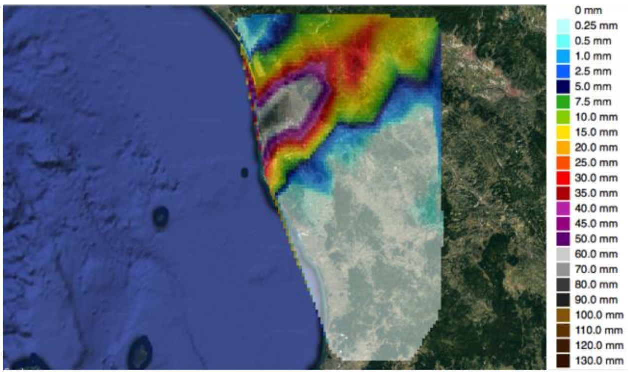

Figure 1. Cumulative rainfall map from 22:15 to 23:45 UTC computed through bilinear interpolation of raingauge measurements.

3.2 The Italian radar network

The Italian operational weather radar network is currently composed of 21 systems, managed by a federation of national and regional bodies including the Department of Civil Protection (DPC), the Air Force, the regional weather services, and the National Aviation Authority. The network is composed of 19 C-band and 2 X-band pulse Doppler radars, 14 of which are dual-polarized. The radar system closest to the area where the event occurred is located on Monte Crocione, a mountain with an approximate height of about 1100 m above sea level, close to the town of Lucca and at about 40 km from Pisa. The software system that processes all the data of the network provides in near real time several composite products as the Constant Altitude Plan Position Indicator (CAPPI), i.e., the reflectivity at a fixed height, the Vertical Maximum Indicator (VMI), the maximum reflectivity value in the vertical column for each pixel, and the Surface Rainfall Intensity (SRI), namely the estimate of rain rate at the surface level. The DPC is responsible for the generation and dissemination of such products at the national level [14, 15]. Figure 2 shows some CAPPI reflectivity maps used in the analysis carried out for this work.

4. The data fusion procedure

The data fusion procedure processes the instantaneous radar reflectivity and raingauge measurements, collected during a given observation time T, in order to compute the rainfall rate $R_T(lat,lon)$ as:

$$\log(R_T(lon,lat)) = A_T(lon,lat) + B_T(lon,lat)\log(Z_T(lon,lat)) \qquad (1)$$

where $Z_T(lon,lat)$ is a time average spatially smoothed instantaneous reflectivity maps gathered during the observation time T, while $A_T(lon,lat)$ and $B_T(lon,lat)$ are function coefficients that are determined through *ad hoc* correlation functions between space-time “average” values of rain gauge data (RW) and radar reflectivity data (ZW).

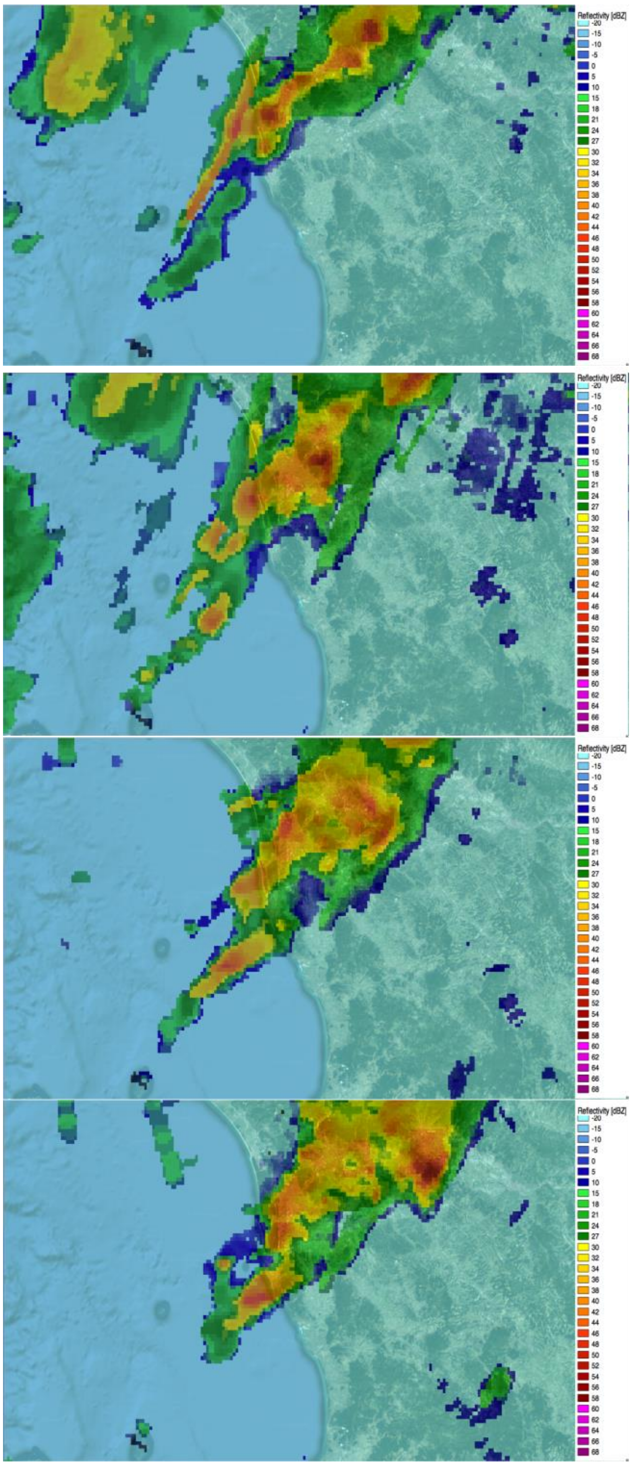

Figure 2. Radar reflectivity at 2000 m (CAPPI) at 22:20, 22:50, 23:10 and 23:30 UTC. Radar data are provided by the Italian National Department of Civil Protection (DPC).

$A_T(lon,lat)$ and $B_T(lon,lat)$ are computed through a space-time 2D bilinear interpolation on the ensembles $A_T(lon_k,lat_k)$ and $B_T(lon_k,lat_k)$, where lon_k and lat_k, $k=1..N_p$, are the coordinates of the N_p raingauges used for correlating raingauge rainfall estimates and radar reflectivities. $A_T(lon_k,lat_k)$ and $B_T(lon_k,lat_k)$ are determined through the regression methods described in [1] and applied to the RW and ZW pairs.

Assuming T=90 min (from 22:15 to 23:45 UTC), we computed the related values of Z_T, A_T and B_T. Figure 3 shows Z_T in the lon-lat grid [10°-11°E, 43°-44°N]. Figure 4 shows the ZW and RW values for all the raingauges within the grid. Then, we computed the cumulated rainfall using (1) (see Fig. 5). Figure 6 shows the difference between the cumulated rainfall estimated only with raingauges data through a bilinear interpolation scheme and that resulting from the data fusion procedure.

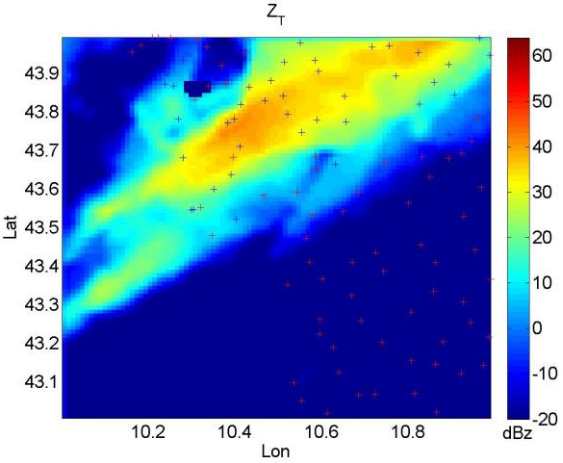

Figure 3. The radar parameter Z_T referred to the interval 22:15 – 23:45 UTC, Sept. 9, 2017.

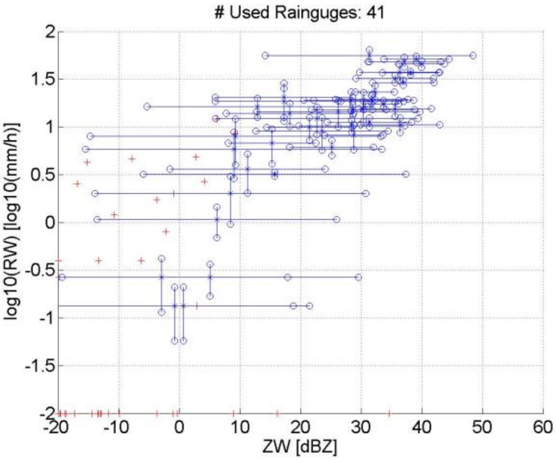

Figure 4. ZW vs RW from 22:15 to 23:45 UTC, Sept. 9, 2017. Blue stars: raingauges (N_p=41) used for radar-raingauge correlation. Vertical blue bar: variability index of the raingauge data. Horizontal blue bar: variability index of the radar data. Red cross: raingauges not used by the data fusion procedure.

6. Conclusions

This work presents a method to improve the QPE based on weather radar using the additional information provided by raingauges for overcoming the problem of the limited quantitative accuracy of precipitation observations as provided by radars that often rely simply on the Marshall-Palmer relationship to convert reflectivity into rainfall rate. The proposed method is an adaptive data fusion technique since it allows adapting dynamically the coefficients of the Z-R relationship to the type of event and to its dynamical development using near real time measurements.

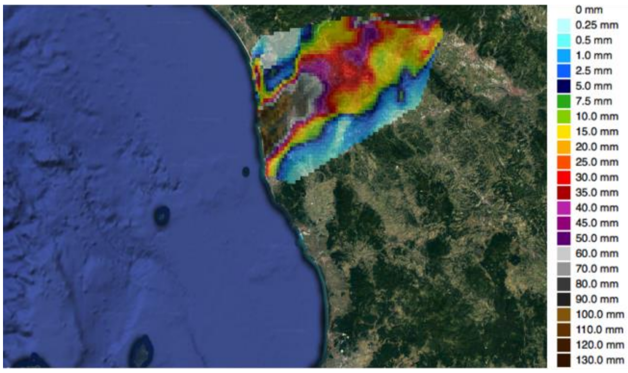

Figure 5. Cumulative rain map R_T from 22:15 to 23:45 UTC computed using (1).

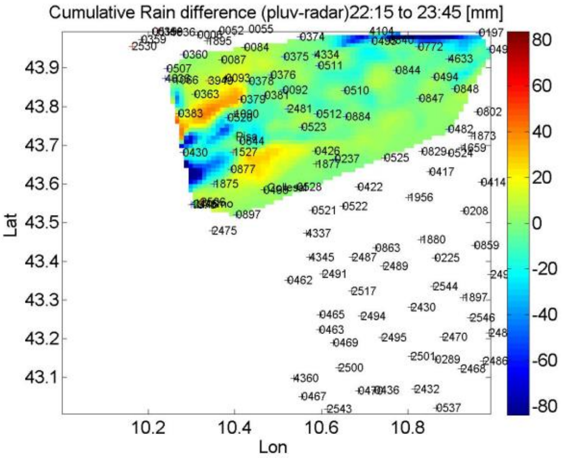

Figure 6. Rainfall difference (Fig. 5 - Fig. 1) between the only-raingauge map and the radar/gauge fusion map.

The method is quite fast and can be used to provide high spatial resolution rainfall estimates, improving the accuracy of radar observations and extending - through a single radar or a network of radars - the coverage of the raingauge network to areas where there are no raingauges displaced, including water surfaces such as lakes and seas. This latter aspect is of particular interest for early warning and nowcasting applications.

An analysis has been carried out through the comparison of the space-time variance of reflectivity with the map of difference between radar and raingauge rainfall estimations. Such analysis showed that raingauges-based maps underestimate rainfall in low reflectivity variance regions, where the precipitation system is stationary and potentially dangerous. In areas where reflectivity shows a higher variability (in both space and time), raingauges precipitation maps overestimate the rainfall

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