A study about the correlation link between lightning data and meteorological data

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Abstract

Lightning Imager (LI) is one of the candidates to fly on the European Meteosat satellite platform of third generation (MTG). Therefore with the MTG it will be available the lightning data on the whole Euro-African zone. The LI is a product of the application field of nowcasting, but the implications of its applications are seen also in hydrology, monitoring of land and forest and management of the crisis. Collaboration between CNMCA (Centro Nazionale di Meteorologia e climatologia dell'Aeronautica) and SELEX-GALILEO (a Finmeccanica company) aims to study a possible methodology use of lightning data, to supply more information about the modalities of LI data in the decision management. In detail this research proposes an algorithm for the identification of convective areas through the use of data LAMPINET (lightning ground network of the Italian Air Force Metereological service), SEVIRI, NEFODINA (a software developed by Italian Air Force Meteorological service that is able to identify convective system and to forecast their developments in the next 15 minutes), radar, and subsequently to characterize the cloud and its precipitation.

Cross-platforms data

For this study, it was used three different data sources: NEFODINA, LAMPINET and italian radar network.
NEFODINA is a model developed by Italian Air Force Meteorological service that is able to identify
Convective system and to forecast their development in the next 15 minutes. This product, composed by a model with a variable threshold and a neural network system, uses a combination of this three MSG channel: 10.8 μm (IR), 6.2 μm (WV1) and 7.3 μm (WV2). It can deduce altitude and morphology of the cloud structure and the brightness temperature of the water vapor in the middle and upper troposphere.
Italian Air Force Meteorological Service set up a lightning network, named LAMPINET, and put it in operation during 2004. The network is based on Vaisala technology with 15 IMPACT ESP sensors distributed on the peninsula and islands. Performances of the network can reach a detection efficiency of 90% and location accuracy of 0,5 km all over Italian area.
Currently, the National Radar Network is composed of 21 radar that work in the C band. The volume made available from each site, with a frequency of at least 15 minutes, is preprocessed according to a set of techniques to de-clutter and resampled at a resolution of 1km. The product of SRI calculates the precipitation to the ground by applying an algorithm on volumetric data of the PPI reflectivity at lower elevation between those acquired which meet the quality criteria in the planning stage. The reflectivity values are converted to measure precipitation (rain rate mm/h) according to the Marshall Palmer equation (Z = aRb) with
a = 200 and b = 1.6.

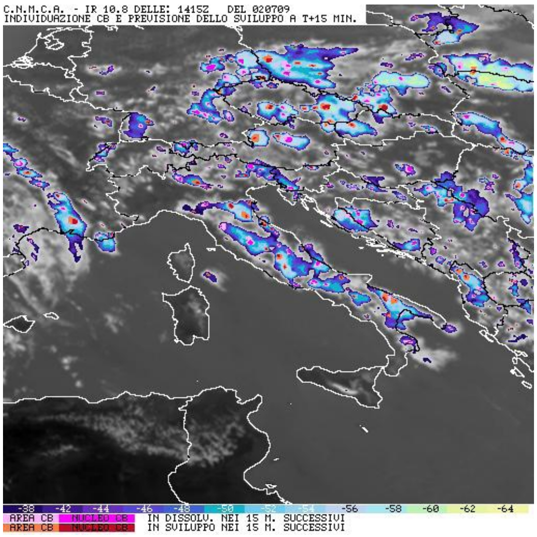

figure 1: **Image of the channel at 10.8 μm prepared by NEFODINA**

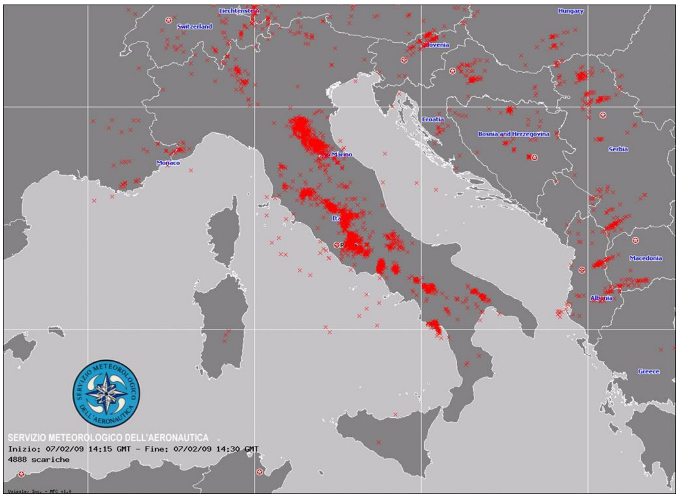

figure 2: **Lightning from Lampinet**

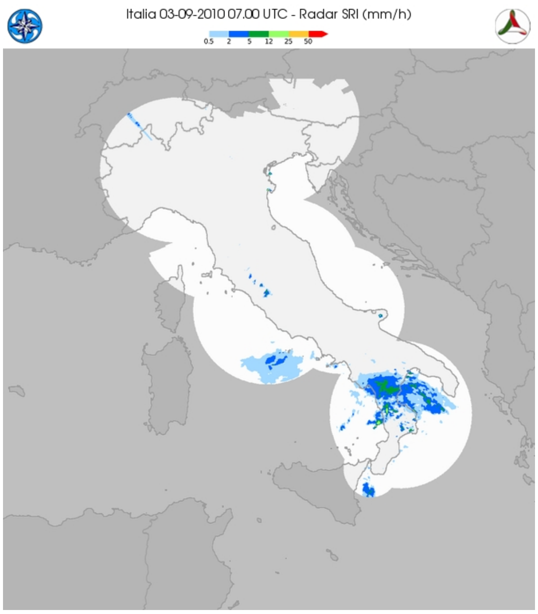

figure 3: **Radar SRI map**

Lightning and convection

Case studies:
Single-cell storm
September 2, 2009, 12:00 – 17:00, Sicily
September 6, 2009, 11:30 - 15:00, Central and southern Italy
September 25, 2009, all day, Central Italy

Multi-cell storm
July 2, 2009, 9:30 - 18:00, Central Italy (on the left)
August 3, 2009, 9:15 - 16:45, North – West Italy
October 11, 2009 10:00 – 17:00 South Italy

Super-cell storm
October 01-02,2009 20:00 – 08:00 South Italy (on the left)

First we have searched presence of electrical activity before a convective cell was detected by Nefodina. Studying single cell storms we have found flashes up to 20 minutes before Nefodina detects a convection activity. In the picture below we see a case of a single cell storm on Adriatic sea; at t = 0 there is the detection of the convective phenomena in developing by Nefodina. This behavior was observed in each case study in the early stage of formation of the storms.

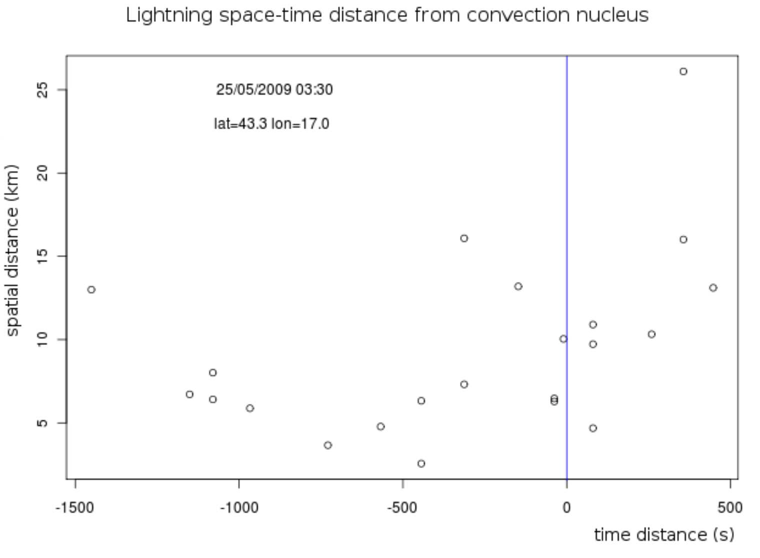

figure 4: **Space-time plot of flash associated to convective event. 05/25/2009 03:30 a.m.**

The second evidence is the uniform distribution of the distances of flashes from convective nuclei. In each case studies we have very few discharges below 5 km, 5% of total discharges, and in the first 10 km around 15%. In this area there is the strongest updraft. The flashes are distributed fairly evenly over the next 30 km with fluctuations of a few percentage points.

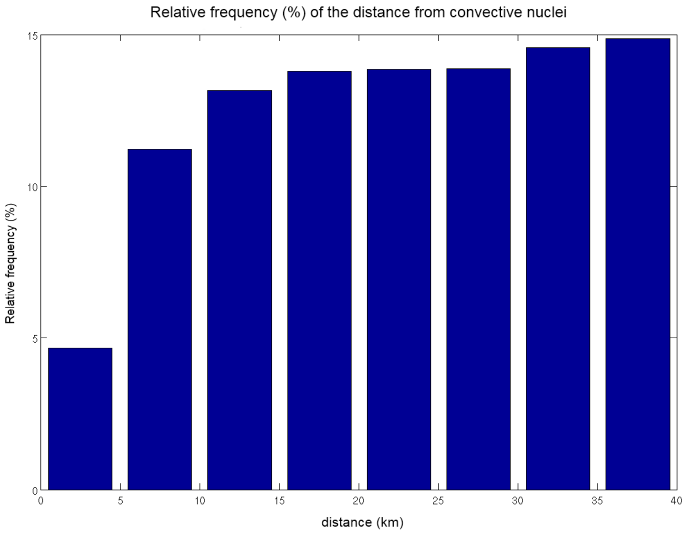

figure 5: **Relative frequency (%) of the distance from convective nuclei**

The third result is that the spatial distribution of lightning around the maximum convection area is not uniform. The electrical activity is stronger in the area between southeast and southwest convection core. Different storms have different angular distribution, sometimes flashes are distributed in southwest area, sometimes in southeast and sometimes this changes during the same storms.

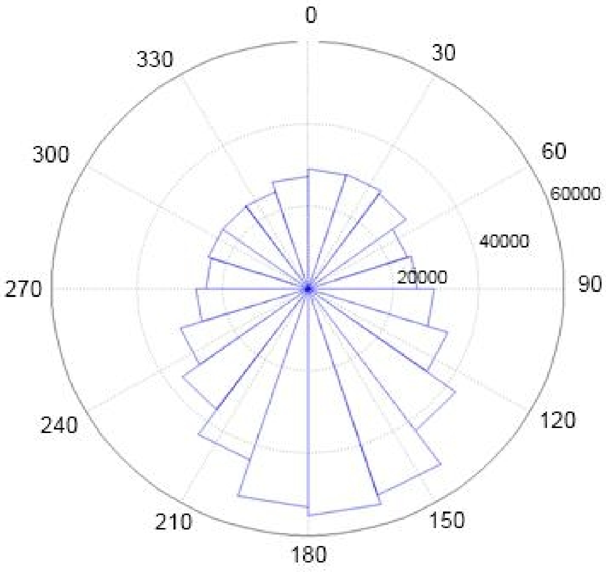

figure 6: **Angular distribution of lightning around convective nuclei**

Lightning – rain relation

There are two ways to estimate rainfall: direct measurement with rain gauge, or using electromagnetic waves with radars or satellites. Radar can measure reflectivity at certain quote getting the rain rate. Recently they are using satellite measure (IR, MW) to rebuild rainfall field. It's important to know rainfall for many reasons. Numerical models for forecasting use the amount of water vapour in atmosphere for their initialization. Latent heating, released during condensation, has a key role in extratropical storms. Then using rain rate in the early stages of numerical simulations, improves prediction of the intensity and pattern of extratropical cyclone. In hydrology, the rains are important for early warning of flood. In fact floods happen 12 – 36 hours after intense thunderstorms (it depends on rivers flow and other factors). In many situations it’s not possible to get a rain measure. There are geographical zones where it's difficult get a good radar coverage because of complex orography or because they are oceanic areas. It seems clear that it's useful obtaining the amount of rainfall in other way like using lightning. From many years it's trying to correlate precipitation and electrical activity, in Uman (1987) there is a good historical review. More recent studies (Sheridan et al., 1997, Petersen and Rutledge, 1998; Soula et al., 1998) show a strong correlation between lightning (CG, cloud to ground) and the intensity of precipitation. In many works (Williams et al., l989; Petersen and Rutledge, 1998; Soula et al., 1998) it was made an attempt to use the electrical activity for the nowcasting of particular intense events or to estimate the precipitations. From the temporal side, Piepgrass et al. (l982) found that the CG lightning flash peak frequency appeared a few minutes earlier than the peak precipitation intensity on the ground in a thunder cell. By analyzing the radar reflectivity and the CG lightning location data, Qie et al. (1993) also found that the peak value of the CG lightning frequency during the development of a thunder cell could be 10–30 minutes in advance of the appearance of hailstones. Tapia et al. (1998) found that the CG lightning flashes usually occur in the strong radar reflectivity region, i.e. in the high precipitation intensity area, while other researchers (Dye et al., 1986; Ge et al., 1995) just in the outside edge of the high precipitation intensity area. It's important to note that high precipitation corresponds to strong atmospheric electrical activity in convective weather systems, but not in stratiform cloud precipitation weather. Tapia et al. (1998) found a quantitative relationship between precipitation and lightning studying 22 thunderstorms in august 1992/1993 in Florida. They used radar data for precipitation rate and a network of sensors at ground for lightning detection. Rainfall-rate data obtained by radars were processed and insert in a 1.0 km grid scale (460 x 460 bins) . The estimation of convective precipitation for a given thunderstorm from the lightning flash observation is based on the use of the following equation that expresses the spatial and temporal distribution of precipitation intensity.

Rainfall-rate maps were computed for the radars area of coverage on a 1.0 km grid scale (460 x 460 1 km^2 bins) . The estimation of convective precipitation for a given thunderstorm from the lightning flash observation is based on the use of the following equation that expresses the spatial and temporal distribution of precipitation intensity.

$$R(t,x)=C\sum_{1}^{N} Zf(t,T_i)\,g(x,X_i)$$

$R(t,x)$	rain rate at time t and spatial location x (mmh^{-1})
N	number of flashes until time $t+\Delta t/2$
T_i	time of the i-th flash
X_i	spatial location of the i-th flash
Z	RLR (rainfall lightning ratio) for the storm (kg per flash)
C	unit conversion factor

The most difficult to determinate is the Z factor (RLR rainfall lightning ratio). After studying 22 cases, Tapia found that RLR has a wide range of values (from 24×10^6 Kg per flash to 365×10^6 kg per flash). It depends on the local climatology and on the kind of convective event. The RLR also changes within the lifetime of a storm. For all of the storms analyzed, the RLR reaches a minimum when lightning frequency peaks. Following this peak, lightning frequency decreases more rapidly than rainfall does, producing higher RLRs as the storm decays. In general, lightning ends before the stratiform rain stage, leading to a poor correlation between lightning frequency and rain flux toward the end of the dissipating stage. In the proposed model the median RLR (43×10^6 kg per flash) of the 22 Florida storms analyzed was used as an estimate of Z.
There is many studies to find a good value for the RLR in different geographic and climatological zone, in Soula (2009) there are a big number of values for RLR.

The temporal distribution is determined by $f(t,T_i)$ as a function of time t from a lightning flash at time T_i, accounting to:

$$f(t,T_i)=\begin{cases}1 & se\ \ |t-T_i|<\Delta t/2\\ 0 & otherwise\end{cases}$$

For this model a Δt of 5 min was adopted. In other words, the precipitation intensity is considered constant during the time interval Δt .
Rainfall is distributed uniformly within a 10-km diameter circle around the location of the lightning flash; that is,

$$g(x,X_i)=\begin{cases}1 & se\ \ |x-X_i|<5\\ 0 & otherwise\end{cases}$$

Accordingly, a single flash produces a rainfall accumulation of 0.55 mm over the 10-km diameter circle.

At each bin, the number of flashes falling within a 10-km diameter circle centered at the bin were counted at 5-min time intervals. This was translated into a 5-min rainfall accumulation at each bin. The time resolution of both radar and lightning derived rainfall accumulations is the same, 5 min. The spatial resolution of the radar reflectivity–derived rain map and that of the lightning-derived map are also the same, 1 km x 1 km.

To evaluate the overall match between both maps in terms of rainfall accumulations, the contingency table approach was used. For each map, a specific bin was declared active or inactive if the rainfall accumulation at that bin was higher than a given threshold. A success occurs when corresponding bins on each map are active; a failure occurs when the bin from the radar derived map is active and the one from the lightning derived map is inactive; and the opposite leads to a false alarm. It uses the *probability of detection* (POD), the *false alarm rate* (FAR), and the *critical success index* (CSI), where these indices are computed as follows:

$$POD=\frac{n_{succ}}{n_{succ}+n_{insuc}} \qquad FAR=\frac{n_{fals}}{n_{succ}+n_{fals}} \qquad CSI=\frac{n_{succ}}{n_{succ}+n_{insuc}+n_{fals}}$$

Potential and limitations of the Tapia's model

Whit this model it can derive an estimate of precipitation for very intense storms. These estimates can be very useful for locations lacking radar coverage and in the correction of radar-estimated rainfall for range effects.

Several sources of error exist in the model, leading to discrepancies in the magnitude of lightning-derived estimates of rainfall. Of these, the most important seems to be the adoption of a unique RLR. The difference in size of the rainy area at low accumulation may be accounted for by the rainfall produced in the stratiform part of the storms, where little or no lightning occurs.

Accumulations higher than 70 mm occur only at the site of the intense storm, where the model overstimates rainfall accumulation (because of the great number of flash) and, thus, rainy area with respect to the radar estimates. When the storm was in its dissipating stage, the lightning had pratically ceased causing the underestimation of the model.

Experimental

To test what it found in scientific literature, it used three cases for which were available radar and lightning data.

- July 2, 2009, 9:30 - 21:00, Central Italy
- August 3, 2009, 9:15 - 16:45, North – West Italy
- September 6, 2009, 11:30 - 15:00, Central and southern Italy

For the data radar it used two different sources. For the case of July 2 and September 6 it was used data radar of the Italian Air Force Meteorological Centre where rainfall-rate maps were computed for the radars area of coverage on a 2.5 km grid scale (560x560 6.25 km^2 bins) . The time resolution of data radar is 30 min. While for the case of August 3 it was used data from meteorological centre of Piemonte where rainfall-rate maps were computed for the radars area of coverage on a 0.8 km grid scale (500x500 0.64 km^2 bins) . The time resolution for this data radar is 5 min.

It has analysed various aspects of correlation between electrical activity and precipitations. First it's studied the temporal correlation between flash frequency and rainfall intensity. It's not found that lightning flash peak frequency appeared a few minutes earlier than the peak precipitation intensity, maybe because of low temporal resolution (30 minutes). In the case of August 3 the temporal resolution is 5 minutes, but the meteorological situation is different. In this case there is an important component of stratiform rain.

The second aspect discussed was the relationship between the mass of precipitated water and the number of discharges, so which gives a direct measure of 'RLR. It found a good linear correlation between these two quantities.

Finally it tried to apply the Tapia model to three cases, with the calculated value of RLR. Observing precipitation maps produced with the model there is a reasonable resemblance to those produced by radar. Instead, the tests with contingency tables have given low scores, highlighting mainly, the spatial area of maximum precipitation does not coincide with that of maximum electric activity.

RLR Rainfall Lightning Ratio

The first aspect to concern is the relationship between the mass of precipitated water and the number of discharges, which gives a measure of RLR. Plotting the mass of the precipitated water in function of the number of lightning flashes, we can derive the RLR through a linear regression. Obviously in this way it isn't taken into account the variability of RLR long development time of thunderstorm, but it takes it steady.

It’s found a good linear correlation between these two quantities in most cases.

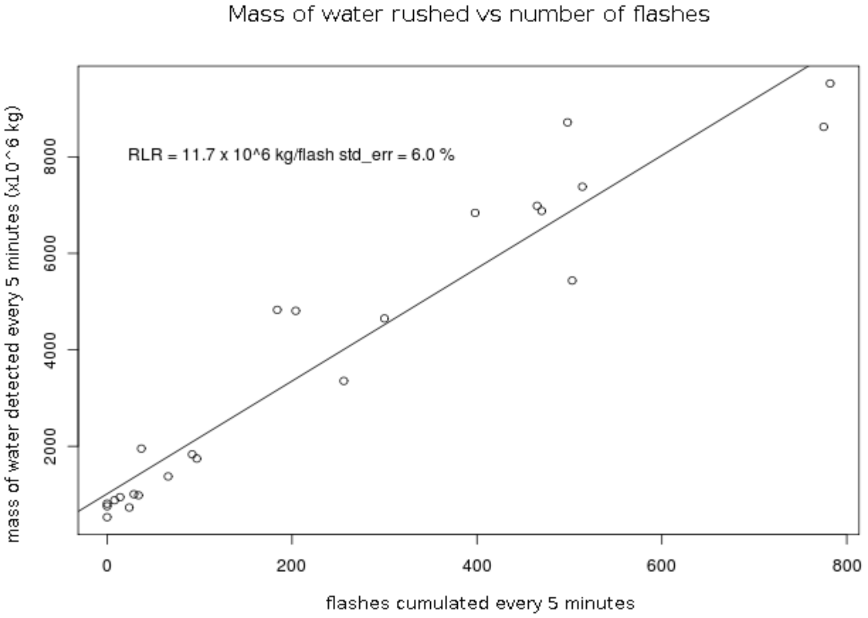

figure 7: **Mass of water rushed vs number of flashes**

The value obtained is RLR = 11.7x106 kg / flash. With this RLR value one tries to apply the Tapia model to see if it’s possible to reconstruct the map of precipitation from only electrical activity. It’s seen that despite a good graphic similarity between the two maps, it isn't not good scores for contingency tables. It's obtained the POD scores ranging between 10% and 20% and the FAR scores between 50% and 60%. Especially the high score of the FAR (which essentially measure false alarms) might indicate the mismatch between the area of greatest precipitation and the one with the highest concentration of flash. This argument still not entirely clear and should be further investigated.

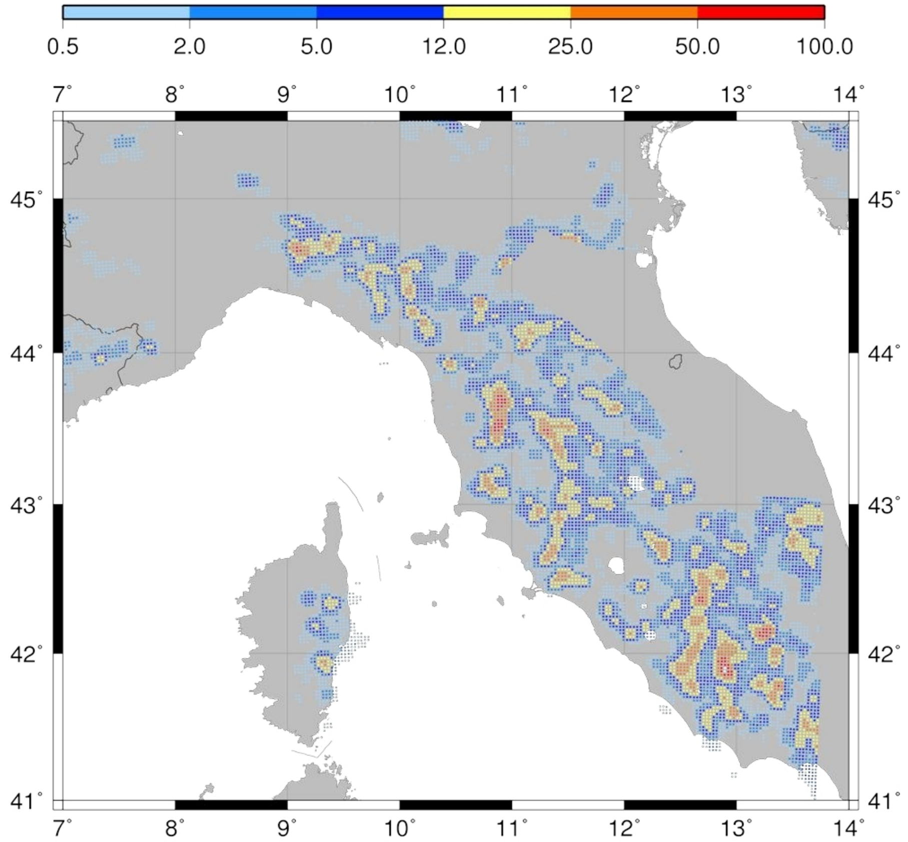

figure 8: **Model map of 12 hours cumulated precipitation**

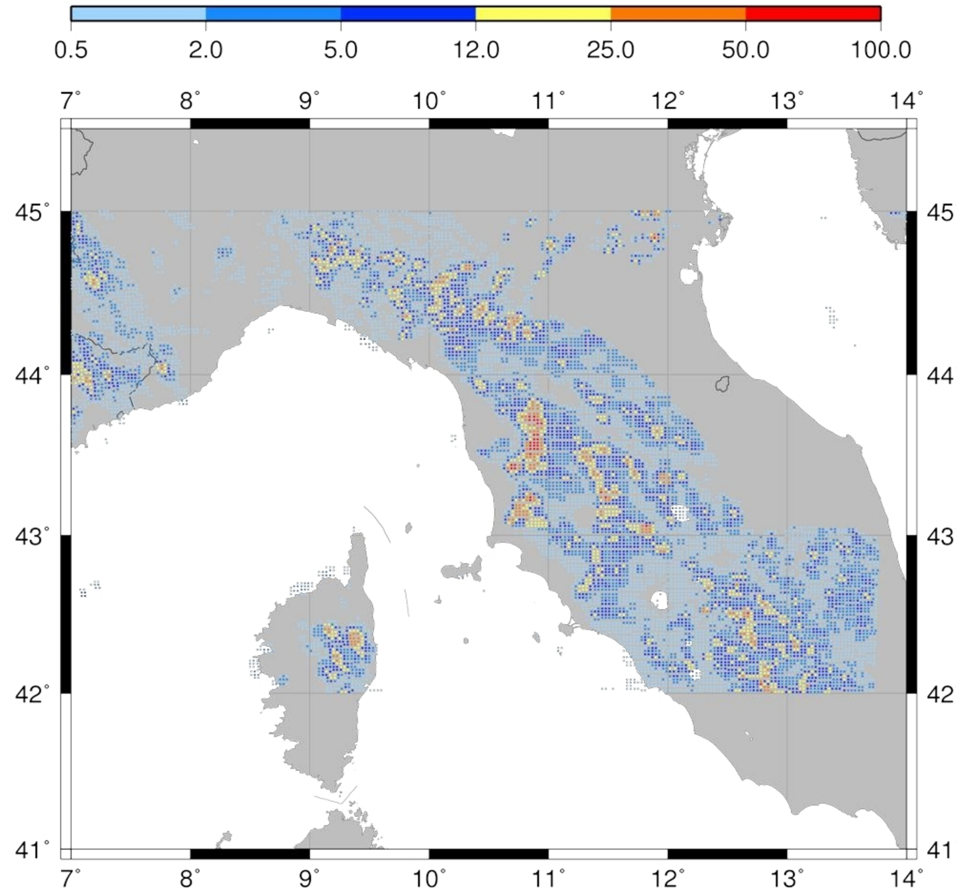

figure 9: **Radar map of 12 hours cumulated precipitation**

The analysis of the images and numerical data outputed from Tapia and Smith model allows for some considerations. The area covered by precipitation is higher in radar maps. The areas with low precipitation (values between 0.5 mm and 2.0 mm, the first two colors on the scale) make the difference, because they are almost absent in instantaneous maps model. It seems that to see the electric stroke is necessary that the precipitation is more intense than this threshold. This is also highlighted in the graph of the mass of water rushed in function of discharge (on the left). In fact, near the origin we can note that there is precipitation in absence of flash and how it is lower than in the next points.

Instead in the maps model there are more extensive areas with high precipitation (> 12 mm areas yellow, orange and dark red). The model correctly identified these zones with strongly precipitating even if it overestimates the area. Apparently besides not coinciding spatially (as shown by scores of contingency tables), the areas with the highest density discharges are more extensive than those at higher radar reflectivity. As mentioned earlier this issue is still not fully understood and under investigation. Several studies, as above, arrive to equivocal conclusions.

Conclusion

This study, starting from the existing scientific literature, tried to identify possible correlations between rainfall and lightning. It has proved that until the convective precipitation is intense the correlation is quite good. The time course of the precipitation intensity follows quite closely the intensity of lightning flash. It highlighted a good linear relationship between the mass of water rushed and the number of lightning. Thanks to this it was possible to get the Lightning Rainfall Ratio (RLR). This important parameter is useful when one wants to reconstruct the spatial map of rainfall from lightning through the model of Tapia. Using this model it has been highlighted some experimental evidence which is still not fully understood theoretically. In particular it was shown that the most dense area of lightning does not coincide exactly with one of precipitation, it also appears to be more extensive. Instead, in areas with low precipitation often there aren't strokes. This behaviour causes the model tends to overestimate some areas and underestimate others. A possible future improvement could be using a dynamic RLR, which varies according to the number of strokes and at least partially it can correct this error. The model, instead, is much less effective for low intensity storms.

The use of flashes can be a good tool to reconstruct the precipitation in all those situations where it cannot use rain gauges or radar. Another interesting development is the use of the data flash as a "correction" of a system based on satellite data (IR, MW, passive microwave) for the reconstruction of the field of precipitation. In this sense, some studies have been completed with encouraging results (Alexander et al., 1998, Grecu et al., 2000,Rosenfeld 2008). In fact the data of the electric discharge helps to overcome those situations where the presence of high cirrus clouds may obscure the underlying presence of convective storms.

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