Severe weather and hail detection using the X band weather radar Tuscany network

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(Dated: 19 June 2018)

1 Introduction

In the last years, an occurrence increment of the weather patterns generating severe thunderstorms was observed for the Mediterranean area. This aspect has been particularly relevant in Tuscany (central Italy) where several heavy rains events leaded to river floods and landslides, especially in coastal areas. Indeed, the synergy of high sea surface temperatures and moist air-masses combined with deep troughs can produce very unstable environments that are favourable to the occurrence of such events.

For a better characterization of these phenomena and for limiting the related risks, a regional X-band weather radar network has been implemented in the Tuscany coastal areas. Three single-polarization weather radars, located in Livorno, Castiglione della Pescaia and Cima di Monte (Elba island), compose the regional network.

Firstly, this work describes the performances of such a network in the monitoring of some precipitation events, particularly intense. The radar composite has been compared with some ancillary data as satellites, raingauges, lightning observations and other radar systems operating in different frequencies (C and S band).

Severe weather systems are sometimes characterized by the presence of hail. Because of its spatial and temporal variability, an accurate detection of hail from ground measurements is very difficult, but an operational hail detection system could be useful for several objectives, from supporting risk management at urban scales to the assessment of damages in agriculture.

Few methods exist for automatic hail detection using single polarization radars, mainly based on the analysis of the vertical structure of reflectivity. Some methods use ancillary data, as the freezing level and the ground temperature, for a better characterization of the microphysics of the maximum vertical reflectivity cell, and consequently the presence of hail.

Two different algorithms, based on the Waldvogel approach and on the Vertically-Integrated Liquid Density (VIL-Density) product, have been tested and compared to assess the capability of such radar network in hail detection with the aim of developing a POH (Probability-of-Hail) index.

Some hail case studies, identified by the Tuscany meteorological office reports, have been analysed and preliminary results concerning the performances of these methods are shown.

2 Radar systems and methodo description

The X-band radar system used for the Tuscany network implementation is the WR10X produced by the ELDES s.r.l company (ELDES, 2018). Three systems constitute the network deployed along the coastal area (i.e., in Livorno, Elba island and Castiglione della Pescaia). At the maximum range of 108 km and with a range resolution of 450m, polar volumes scans are acquired every 15 minutes at ten elevations: from 0.5° to 5.0° at 0.5° steps. The radar systems are single polarization and non Doppler. Therefore, as well as a signal processing chain and 3D geolocation procedures, suitable filters for sea and land clutter removal have been implemented, as described in (Antonini, et al., 2017). A composite is available for integrating all the information in a single product for the observation of precipitation systems. A 2D composite is created assigning the highest reflectivity value in any overlapping points of the selected area. The maximum reflectivity values allow an immediate evaluation for each pixel of the intensity of the event, also used to activate early warning and preventive procedures.

The available products used for monitoring real time phenomena are the Horizontal and Vertical Maximum Intensity (HVI), VMI, PPI, and the Range Height Indicator (RHI). These products allow a continuous monitoring of the 3D structure of the atmosphere for weather observation and nowcasting purposes.

During the intense weather phenomena the radar instruments can help the assessment of the microphysical structure of the meteorological events. The radars scan strategy is organized to operationally perform a RHI scan pointing towards the direction where the nucleus of higher reflectivity values is present. The RHI gives an immediate view of the vertical structure of the precipitation system. Heavy rain systems are very often characterized by an inner nucleus of reflectivity values higher than 45-50 dBZ, surrounded by lower values and generally decreasing in function of height. The localization and identification of these very high reflectivity nucleuses plays a crucial role for the processes of rainfall rate calibration,
mitigation of overestimation errors and hail detection (Smith, 1998). An extremely important source of error for heavy rainfall events is the significant influence of the elevation angle that cause an enhancement of reflectivity when sampling in the brightband. Additional complexity is introduced by the presence of hail.

In deeply convective thunderstorms the vertical development of the clouds consists of droplets (both liquid, water and ice crystals) distributed from the surface level to the top levels, up to 10 or more kilometers. Three main layers can be identified in the cloud vertical structure: the lower is a warm layer with temperatures above 0°C, where the droplets are in the liquid phase; an intermediate level is the supercooled, mixed, above the thermal zero (freezing level) at a temperature lower than 0°C where droplets are both in liquid and ice phase and finally the higher level is the cumulonimbus anvil, at a temperature lower than -40°C, with only ice crystal (Agency Suppression Hail).

Sometimes, in these conditions of strong vertical motions, liquid droplets can be pushed to heights with temperatures below 0°C and they come to thermodynamically instable supercooled condition. The hail formation processes are not completely understood, but some microphysical conditions are necessary for the hail precipitation formation: supercooled liquid water content in the cloud; hail embryos (Knight & Knight, 1970): small frozen raindrops growing by the effects of the surrounding thermodynamic instability of particles; and finally strong updraft motions.

The identification of the presence of hail is much simpler and more reliable using doppler and polarimetric radars and some algorithms exist allowing to define a probability that the storm is characterized by hail (POH – Probability Of Hail).

In the hailstorm some important features are present that have been used for the implementation of hail detection algorithms. The most important indicators are the presence of a reflectivity core of 50 dBZ or higher somewhere between 5 and 12 km altitude far above the freezing level, and the presence of radar echotops higher than 8 km.

Several algorithms exist for the detection of hail using single polarization weather radars, and some studies have been made for their comparison and their skill characterization (Holleman, 2001) also focusing on X-band systems (Capozzi, Picciotti, Mazzarella, Budillon, & Marzano, 2016).

In hail detection algorithms applied to single-polarization radars an analysis of the Vertical Profiles of Reflectivity (VPR) is implied, over the site of POH estimation. The estimation of the correct height relative to the measured reflectivity is strongly affected by error due to signal propagation in the atmosphere, resulting in uncertainties in hail (Delobbe & Holleman, 2006). Fortunately the large number of elevations (10) collected at every timestamp by the X-band Tuscany radar network, very often allows the estimation of the VPR for hail detection purposes.

VIL is a nonlinear function of reflectivity and converts weather radar reflectivity data into estimates of equivalent liquid water content based on theoretical studies of drop size distributions and empirical studies of reflectivity factor and liquid water content (Greene & Clark, 1972). VIL is a radar-derived estimate of liquid water in the vertical atmospheric column. VIL density (VILD) is the VIL divided by the echo top height, and can be used to identify storms with high reflectivity values relative to their heights, that are very often characterized by hail (Amburn & Wolf, 1997). The increment of VILD is strongly correlated with the increment of hailstone size and quantity. Given the VILD in g m⁻³, the probability of hail occurrence is defined as a cubic function. In this work we will adopt the coefficient derived in (Capozzi, Picciotti, Mazzarella, Budillon, & Marzano, 2016), resulting from the analysis of VILD measured for about fifty strong storms in the Gulf of Naples from 2012 to 2015:

$$POH (VILD) = 0.009344 \ VILD^3 - 0.1106 \ VILD^2 + 0.5057 \ VILD + 0.05351 \quad (2.1)$$

Most of methods used for the detection of severe weather are based on the maps of VMI, where for each pixel the maximum reflectivity values on the vertical column are represented. Reflectivity values exceeding 50dBZ very often indicate heavy rainfall (Auer Jr., 1994). A first indication of the hail presence is given by the vertical location of the higher reflectivity values. To permit the hail formation process the maximum reflectivity must be above the freezing level. Moreover the Waldvogel method for the detection of hail uses the maximum altitude at which a reflectivity of 45 dBZ is found (HZ45) in relation to the height of the freezing level (H₀) (Waldvogel, Federer, & Grimm, 1979). Given $\Delta H$ as the difference between HZ45 and H₀ (in km):

$$POH (\Delta H) = 0.319 + 0.133 \Delta H \quad (2.2)$$

The principal source of data for this study is an archive of volume scan reflectivity observations from the X-band Tuscany weather radars, but the analysis has been made also comparing those observations with all the other available data sources: data from other radar systems operating in different frequencies (C- and S-band), a dense raingauge network of more than 400 point measurement over the region, the lightnings occurrence information, satellite imagery. Finally the WRF NWP model is used to estimate the freezing level and to compute the vertical extension of the systems. Some severe weather and hailstorm cases will be presented and discussed in the next sections.
3 Case studies analysis

The Tuscany regional network is operational since 2012, when the first radar has been installed. During these years several precipitation events have been observed. A selection of recent heavy rain and hail events detected by the weather radars is presented and discussed.

3.1 Versilia strong rainfall event (2016-11-18,19)

This weather event originated from a perturbation on the Algerian and Tunisian coasts that activates a flow of mild and humid air over Tuscany. From the afternoon of 18th November and especially in the evening abundant precipitation occurred in the northern areas, in Lunigiana and Garfagnana. An intense perturbation, connected to a vast Atlantic trough, affected the central Mediterranean area. Heavy rains occurred between night and next morning. Maximum rainfall punctual values up to 200 mm (150-175 mm in 6 hours) in Lucca and 100 mm on the Apennines of Pistoia and Massa, where registered. This intense rainfall amount caused a flood wave of the Versilia River fortunately resolved without damage and without flooding. During the night the precipitation system propagates southerly.

Figure 1 presents a series of images collected from different weather radar systems (C, S, and X band) observing the precipitation phenomena.
As compared with raingauges observations the event is well detected by all the radar systems, also in the qualitative assessment of the intensity. The longitudinal section of the main precipitation system (the one to the north) is observed with high correlation, also over sea. Higher accordance is given by X and C band systems, with reflectivity values up to 50 dBZ. The longitudinal cells with very low intensity are not detected by C band national network, but are present in the X-band and S-band measurements. Finally the reflectivity intensity of the southern system seems quite high in C-band radars. The reflectivity fields resulting in the X-band mosaic are very clear of noise, and in some areas the precipitation is not detected. C and S band systems instead seem to overestimate the precipitation resulting in a minor detail, due to the lower resolution, as compared to X-band.

3.2 Arcidosso hail case study (2018-06-08)

On 8th June 2018, in the area of Arcidosso, a little municipality located in the weastern valley of the Amiata Mountain a violent storm has caused damage and several flooding and teams of firefighters had to act for some calls from some citizens. A strong hailstorm also fell, causing damage to gardens and crops. The most probable occurrence time of the hailstorm is around 12:00 UTC. The storm propagated in the southwest direction involving large areas. The Castiglione weather radar is located very near and has allowed observing and monitoring the evolution of the event. The images of the storm are presented in Figure 2, where the HVMI and the RHI products are shown.

![Figure 2: Radar observations of the hailstorm occurred in Tuscany on 8th June 2018, time 12:00 UTC. HVMI (a) and RHI (b) products are depicted](image)

The HVMI shows the different precipitation cells, and the one with the greatest intensity is easily identifiable. RHI image is a section of the storm. Unfortunately this section is not exactly spatially coincident with the maximum values of reflectivity, but the vertical structure of the storm is well reconstructed, showing a very strong vertical development. During the event the freezing level (H₀) was quit height, as often happens during the summer season. No radiosoundings are located near the event, and for a better assessment of the microphysical structure of the cumulonimbus the freezing level value has been obtained from the WRF model output, providing the value H₀ = 3200m at the time of the storm occurrence.

The HVMI image shows the conical shape of the reconstructed scenario. This is due to the scan geometry. The maximum operational elevation is 5°, and is not sufficient to cover all the vertical extension of the storm. As the storm is located at about 45km from the radar site with an elevation angle of 5° the maximum height of a measured reflectivity cell (echotop) is about 5000m. This is about a half of the real storm echotop that is over 9000m, as suggested by the RHI image.

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The estimation of the AH (Figure 3.b), with a threshold of 1.4km, as suggested in (Waldvogel, Federer, & Grimm, 1979), perfectly localizes the hailstorm. The extracted value is ΔH*1.9km, which provides a POH(ΔH) * 60%. The VILD (Figure 3.c) observed in a later moment (14:00 UTC) of the time series of the event, is about 2.4 g/m³. The related POH(VILD) is 75%. The underestimation of the POH(ΔH) is due to the underestimation of the HZ45. By extrapolating the correct value from the RHI or the VPR, a plausible value of the HZ45 seems to be around 6500m, and the corresponding POH(ΔH) * 75%.

The VPR also suggests a probable underestimation of the VILD in the related timestamp, due to an incomplete sampling of the vertical structure of the higher reflectivity nucleus.
Finally it should be noted that it is not very clear the impact of high values of freezing level, combined with the liquid water in determining the hailstorms.

3.3   San Marcello Pistoiese hailstorm (2015-06-23)

This weather event is characterized by a transit of a fast perturbed system preceded by a mild and humid flow in the lower layers of the atmosphere, and several thunderstorms during the night with hailstorms and strong winds. The orographic triggering of convection and precipitation plays a crucial role.

Also in this case there is a strong vertical development of the precipitation system. Due to the distance from the observing radar systems the event is well reconstructed from reflectivity volumes and cross sectional observations (see Figure 4).

Figure 3: Radar observations of the hailstorm occurred in Tuscany on 8\textsuperscript{th} June 2018. Network composite (a) Estimation of the $\Delta H$ (b) VILD estimation (c) Vertical Profile of Reflectivity

Figure 4: Radar observations of the hailstorm occurred in Tuscany on 23\textsuperscript{rd} June 2015. HVMI (a) and RHI (b) products are depicted
The freezing level estimated from the WRF model is $H_0=3000\text{m}$. The cells imputed for hail occurrence are very localized. The $\Delta H$ values are up to $4000\text{m}$, with a $\text{POH}(\Delta H) = 80\%$. In this case the VILD is about $1.2 \text{ g/m}^3$ and the $\text{POH(VILD)}$ is $50\%$.

![Image a)
](image)

![Image b)
](image)

![Image c)
](image)

![Image d)
](image)

*Figure 5: Radar observations of the hailstorm occurred in Tuscany on 23rd June 2015. Network composite (a) Estimation of the $\Delta H$ (b) VILD estimation (c) Vertical Profile of Reflectivity

Also for this case the same considerations apply, as the reflectivity profile is strictly increasing up to $8000\text{m}$ and the height of the tower seems to be above $11\text{km}$.

3.4 Torrita di Siena flood case study (2018-05-08)

Due to a structured weather system some intense and very localized precipitation phenomena affected the internal areas of the region, between Florence, Siena and more south. The precipitation caused several damages as torrents overflows flooding of roads, and block of the railways. The comparison of C and X-band radars (Figure 6) highlights some matching and some differences. A perfect accordance exists in the shape of the main precipitation cell.

![Image a)
](image)

![Image b)
](image)

*Figure 6: Radar observations of an intense event occurred in Tuscany on 8th May 2018. Time 15:00 UTC. C-band national mosaic (a) and X-band Tuscany mosaic (b) are depicted*
In this main cell C band radars images provide almost exclusively values around 50dBZ. However, the weather reports and the raingauges network observations show that the core of the system with greater intensity was rather localized. X-band radar observations provide values more differentiated within the cell, due to better spatial resolution, and the different intensities of precipitation are well identified. On the other hand the X band measurements lose the widespread rainfall fields, associated to lower reflectivity values (around 15dBZ), and corresponding light precipitation rates. This weak precipitation is not actually present in all the areas indicated in the C band composite, confirming a tendency to enlarge the patterns of light precipitation fields.

3.5 Impruneta hailstorm (2018-03-07)

A deep depression on the British islands trigger humid and unstable currents towards Europe and the Mediterranean. A frontal system transits in Italy with a mild south-western flow in the lower layers combined with the entrance of air gradually colder at high altitude. In this framework high instability is associated to the weather system, with some strong convection activities associated to intense hailstorms. Figure 7 shows the observations of the hailstorm using a X-band dual polarized weather radar.

![Figure 7a: X-band polarimetric radar observations of a hailstorm occurred near Florence (Impruneta) on 7th March 2018. Time 9:10 UTC. VILD (a) and polarimetric observation of the precipitation type (b)](image)

The polarimetric reconstruction of the precipitation type (Figure 7.b) localizes the area of hail occurrence, and is used for the visual validation of the VILD-based identification of hail. In this case the VILD is very high (values from 3.5 to 5 g/m³) and the corresponding POH(VILD) spans from 70% to 85%. For this event, although occurred in a winter season the freezing level as obtained from the WF model is around $H_0=1600$ m.

4 Conclusions and remarks

This work describes some cases of very intense precipitation occurred in Tuscany as observed from the X band radar network. The usefulness of these systems for operational meteorological vigilance is corroborated from the results shown. Two algorithms for detecting hail in single polarization radar have been implemented and compared, one based on the cloud liquid water content, with respect to the echotop, and the other based on the vertical structure of the cloud tower, and in the height difference between high nucleus and freezing level. Both algorithms provide useful information for an early assessment of hail precipitation occurrence, with some related uncertainties.

To further explore the potentialities of such algorithms some further case studies, in a systematic analysis should be studied, by introducing a larger number of recorded hail cases. A big contribution could be given by using hail occurrence data as obtained by media communication, for a better space and time localization of phenomena.

As in some cases the radar volumes cannot cover all the 3D extension of the systems, the scan strategies should be modified to increment the possibility of observing the true vertical extension of the deep convection, elevations up to 10° should be included in the scan.

Moreover it is evident, also from literature that the probability of hail depends strongly on the height of the freezing level. When the freezing level is at lower height the probability of observing hail increases. However, many hail events occur in summer when the freezing level is typically above 2500 m. Some studies about the zonal climatology of such events should be conducted for a better assessment.

References