Polarimetric signatures of Mediterranean storms retrieved by an operational X-band radar system

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1 Introduction

In addition to the advantages derived by their generally compact dimension, transportability and affordable cost, the maturity of dual-polarization technology and related processing methodologies are making X-band radar systems more and more appealing instruments, even for quantitative operational applications. In Mediterranean region, especially in coastal areas, risks (such as localized flooding or triggering of landslides) is often determined by convective systems that are characterized by extremely localized and short-duration heavy precipitation with intense rainfall, often mixed with hail. In addition, weather radar networks made of C-band radars in certain regions may present some unavoidable gaps determined by the orography. The use of shorter range X-band radar is an attractive solution to fill these gaps and to provide high resolution data in risky areas. However, the use of X-band radar for monitoring such events still presents challenging issues. Some authors already used X-band observations for rainfall estimation during intense precipitation events (Matrosov et al., 2005; Anagnostou et al., 2010). Matrosov et al. (2013) also exploring the utility of X-band polarimetric radar observations for convective-rainfall estimations in presence of rain-hail mixture.

This paper describes how X-band radar can be effectively used for such events. In particular, it describes, in terms of their radar polarimetric signatures and radar retrieved rainfall fields, a couple of severe hail-bearing Mediterranean storms occurred in 2013 in South Italy and observed by an X-band dual polarization radar operating inside the Catania airport (Sicily, Italy) and managed by the Department of Civil Protection. On 21 February 2013, a convective system originated in the Tyrrhenian sea hit only marginally the central-eastern coastline of Sicily (Italy), causing the flash-flood of the city of Catania. The optimal radar location (the system is located at just few kilometers from the city center), enabled to well reconstruct the storm characteristics. On 21 August 2013, a mesoscale convective system originated by the temperature gradient between sea and land surface lasted some hours and eventually flooded the city of Siracusa (south-eastern Sicily) with about 180 mm of rainfall as registered in two hours by the nearby rain gauge. Absolute and differential attenuation are dealt with differential phase measurements properly processed through an iterative approach using a short length moving window. The attenuation correction algorithm parameterization is derived by 3-years of DSD observations collected by a disdrometer in Rome. A Fuzzy Logic hydrometeor classification algorithm was also adopted to support the analysis of the storm characteristics. Extemporaneous signal extinction caused by close-range hail core causing significant differential phase shift in very short range path is documented. The localized peaks of precipitation amount were well reconstructed using a combined polarimetric rainfall algorithm based on reflectivity and specific differential phase.

2 Methodology

The system used for observation is a SELEX-Gematronik 50 DX dual-polarization radar with a 3-dB beam width of 1.3 ° and 50 kw of peak power. The radar was deployed at the airport of Catania by the end of 2010 and is currently integrated as gap filler within the national radar network. The operational observation strategy includes 12 PPI scans, from 1 to 21.6 degrees of antenna elevation, repeated every 10 minutes. Vertical scanning are also performed in the presence of precipitation over the site. The adopted PRF is 1875 Hz, which corresponds to a maximum unambiguous range of 80 km, while the range resolution is 200 m. Due to the presence of the Etna volcano, whose peak (about 3.2 km above sea level) is located at about 30 km north from the radar, a wide azimuth sector (about 90 degree) is shielded at low elevation scans. At 3-deg elevation, the shielded sector shrinks to about 20 deg of width, becoming almost negligible at 5 deg.

The radar data are processed to deal with the main uncertainty sources, as schematically summarized in the following.

- *Differential reflectivity calibration*. Z_{DR} is calibrated through vertical scan observations resorting to the hydrometeors properties (Gorgucci et al., 1999).
- *Ground clutter identification*. A Fuzzy-Logic based approach resorting to the concept of data quality is applied (Vulpiani et al., 2012);
- *Specific differential phase retrieval*. This is a very crucial step considering that specific differential phase is a precious radar parameter in rainfall estimation, it being immune to system calibration, attenuation and partial beam blockage. Notwithstanding, K_{DP} remains an estimated quantity whose reliability depends on the system noise and, of course, on the adopted estimation technique. An iterative moving-window range derivative

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approach is applied here, which enables, on one side, to easily remove the offset on Φ_{DP}, facilitating the application of any attenuation correction procedures, and, on the other side, to control the expected K_{DP} standard deviation (Vulpiani et al., 2012). It is worth mentioning that a 1.6-km moving window size, within a three-fold iteration scheme, is here applied to properly reconstruct the remarkable differential phase shift gradients.

- *Attenuation correction*. A linear relationship $\alpha_{H,DP} = \gamma_{H,DP} K_{DP}$ between specific differential phase and specific copolar (α_H) and differential attenuation (α_{DP}) is applied (Bringi et al. 1990). The multiplicative coefficients (γ_H=0.292 dB/deg, γ_{DP}=0.048 dB/deg) have derived by more than 3-years (June 2010-December 2013) of DSD observations collected by a Parsivel disdrometer istalled on the building hosting ISAC-CNR in Rome (Adirosi et al., 2014). It is important to specify that in the present work, the dependence of $\gamma_{H,DP}$ to drop temperature and drop size (Jameson, 1992) is not taken into account through potential optimization approaches (Carey et al., 2000; Vulpiani et al., 2008).
- *Rainfall estimation*. A polarimetric algorithm based on the combined use of reflectivity factor and specific differential phase, the latter being exploited for moderate to high rainfall regimes. The combined algorithm proposed in Vulpiani and Baldini (2013) is here applied. It has the form of a weighted sum

$$R = w_K R_K + (1 - w_K) R_Z \quad (1)$$

where R_Z and R_K are the rainfall estimates obtained using Z and K_{DP} through the power laws proposed by Marshall and Palmer (1948) and Matrosov et al. (2005), respectively. The weight w_K is defined as

$$w_K = \begin{cases} 0 & \text{for } K_{DP} \le 0.5 \\ 2 \cdot K_{DP} - 1 & \text{for } 0.5 < K_{DP} < 1 \\ 1 & \text{for } K_{DP} \ge 1 \end{cases} \quad (2)$$

in such a way that R_K is considered not reliable for K_{DP} lower than 0.5 deg km^{-1} , partially reliable in the range 0.5≤K_{DP}<1 and fully reliable for K_{DP}>1.0 deg km^{-1}:

3 Cases Study

3.1 Signal extinction due to rain/hail mixture: the 21 February 2013 case study

A severe supercell with associated lightning, originated in northeastern Sicily (Italy), flash flooded the city of Catania (central-eastern coast) on 21 February 2013. The observed storm reached the maximum intensity overland between 1500 and 1600 UTC. According to press reports, liquid precipitation was also accompanied by hail. Fortunately, the storm developed mainly on sea causing only localized effects on the ground. Indeed, the rain gauge located in Catania registered about 60 mm in 1 hour between 1500 and 1600 UTC and about 70 mm in 1 and half hour. Whereas precipitation observed by nearby stations did not exceed 20 mm in 3 hours. Figure 1 shows the Vertical Maximum Intensity (VMI) (X-band attenuation correction is applied), at 1500 UTC, when a strong convective core approached the city of Catania. An apparently shielded sector is clearly visible in the north-north-eastern direction. However, in that direction the radar visibility is good starting from 2 deg of antenna elevation. The measured (attenuated) reflectivity reached almost 60 dBZ at about 5 km from the radar, while the return "disappeared" at the lowest antenna elevation angles at about 13 km from the radar. This was likely related to strong attenuation effects and not to partial beam blocking. To validate this hypothesis, pseudo RHIs of the polarimetric observables and the corresponding hydrometeor types as resulting from classification are examined in Figure 2 relatively to the 4-deg azimuth angle. Looking at Z and K_{DP} shown on panel a) and d), 3 convective cores are identifiable at about 5, 8 and 10.5 km, respectively. The differential reflectivity is relatively high within the first core, exceeding 3 dB, while the correlation coefficient drops down to about 0.95. These signatures might be compatible with the presence hail, melting hail and large drops, identified as hail rain mixture class (dark red) by the adopted hydrometeor classification scheme (Figure 3). The signature of hail or rain-hail mixture is still noticeable within second convective core, still characterized by reflectivity exceeding 50 dBZ but with higher K_{DP} (about 15 deg km^{-1}) and slightly lower Z_{DR} and ρ_{HV}. The increase in K_{DP} might be symptomatic of higher water fraction within the rain-hail mixture or hail water coat thickness. The presence of moderate values of Z_{DR} (about 1dB) could be related to uncompensated attenuation. However, at low elevation angles, beyond the third convective cell, the radar signal abruptly "disappeared". This is clearly visible on Figure 4 showing the range plots of the polarimetric observables at 6 deg of antenna elevation. The measured reflectivity is shown on the upper panel together with the corrected one. The Minimum Detectable reflectivity (MDZ) is also superimposed. It can be noticed that the measured reflectivity drops down at about 13 km from the radar, assuming values close to the MDZ. The data were rejected at signal processor level. The effects of decreasing SNR caused by attenuation are also traceable by the decrease of the correlation coefficient. It is also noticeable that, because the dynamic range of Z_{DR} was set by default between -5 and 15 dB, Z_{DR} reached the bottom scale at about 9 km assuming, thereafter, a plateau-like profile. Consequently, the corrected Z_{DR} profiles appear unrealistic.

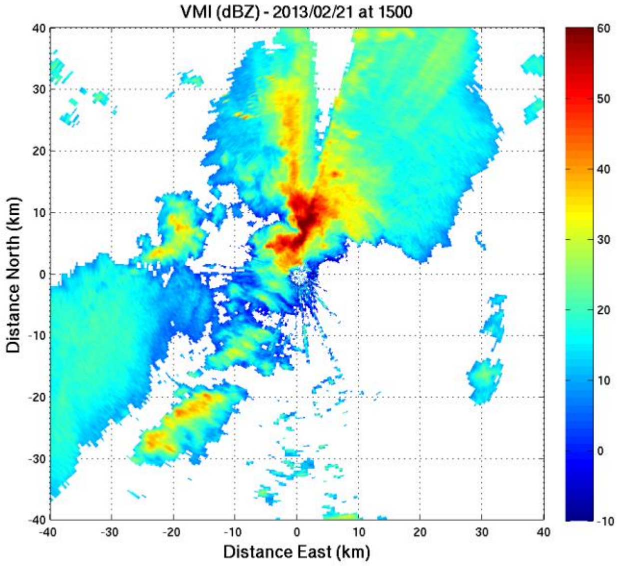

Figure 1:Vertical Maximum Intensity (VMI) displaying the supercell observed on 21 of February 2013 at 1500 UTC.

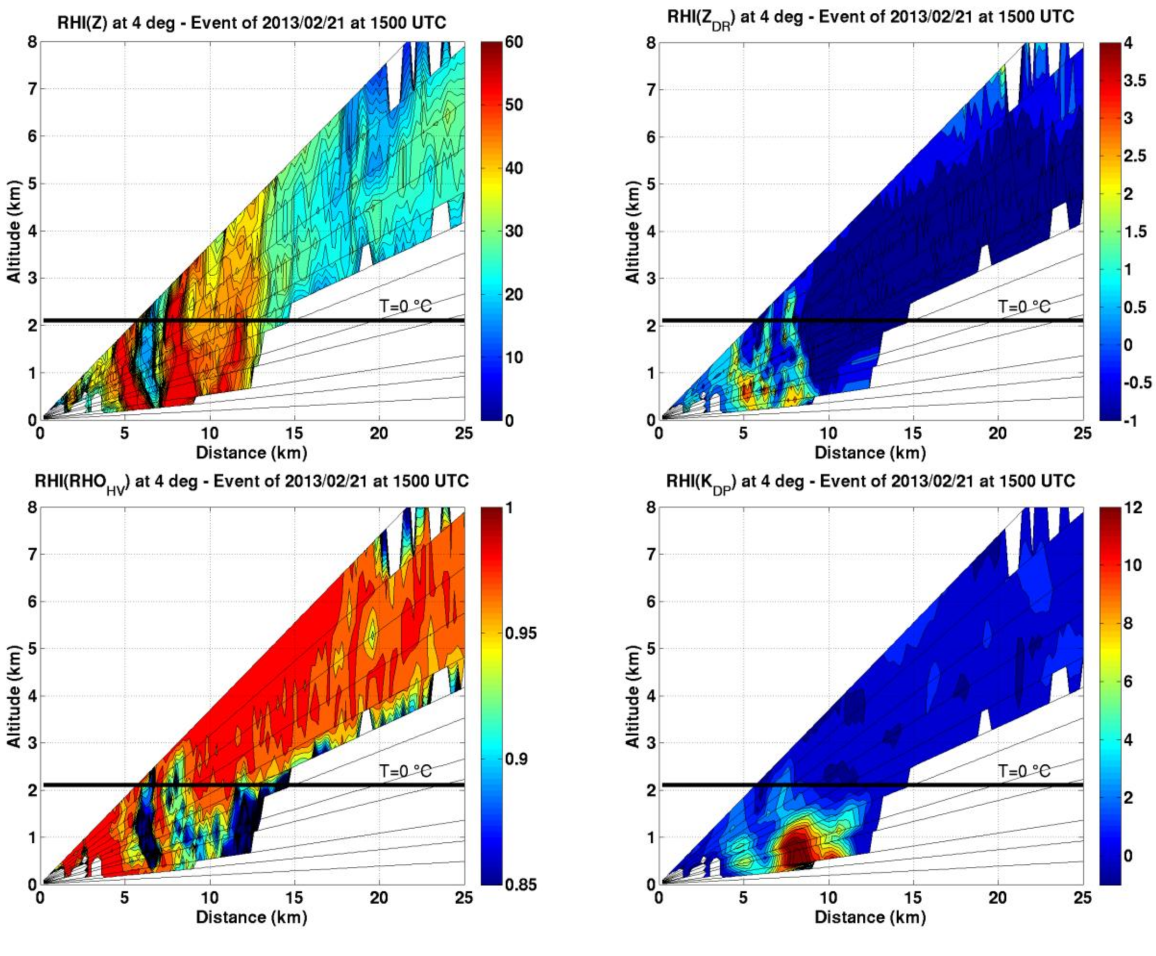

Figure 2:Pseudo RHIs taken at the 4th-deg of azimuth relatively to the polarimetric variables observed on 21 February 2013 at 1500 UTC. The horizontal line shows the approximate height of the Freezing Layer as retrieved by vertical radar observations at 1650 UTC.

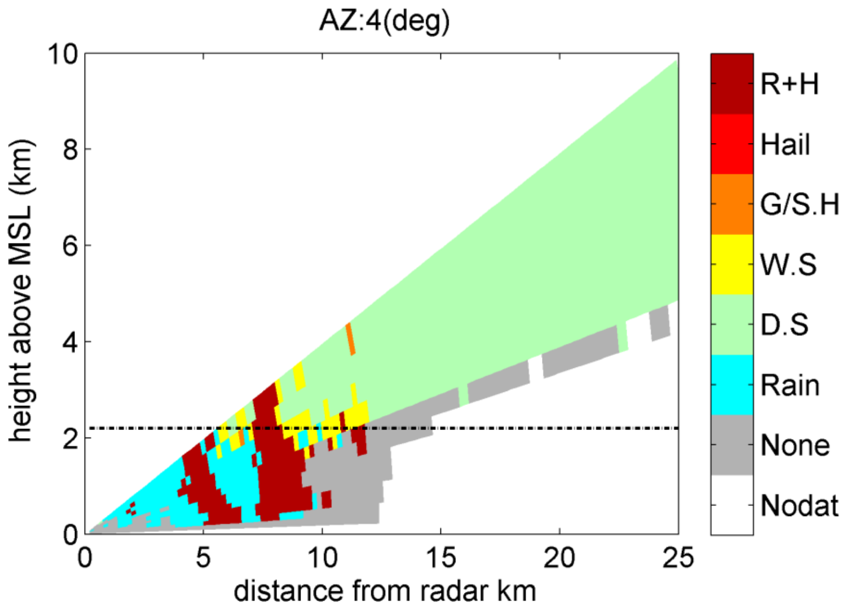

Figure 3. Hydrometeor classification applied to pseudo RHIs taken at 4-deg azimuth on 21 February 2013 at 1500 UTC obtained by Fuzzy Logic classification algorithm (Liu and Chandrasekar 2000) adapted for X-band. The horizontal dotted-dashed line shows the approximate height of the Freezing Layer as retrieved by vertical radar observations at 1650 UTC. The classes detected are: Rain (light blue), Dry Snow(green) Wet Snow (yellow), Graupel and Small Hail (orange), Hail(Red), Hail rain mix (dark red).

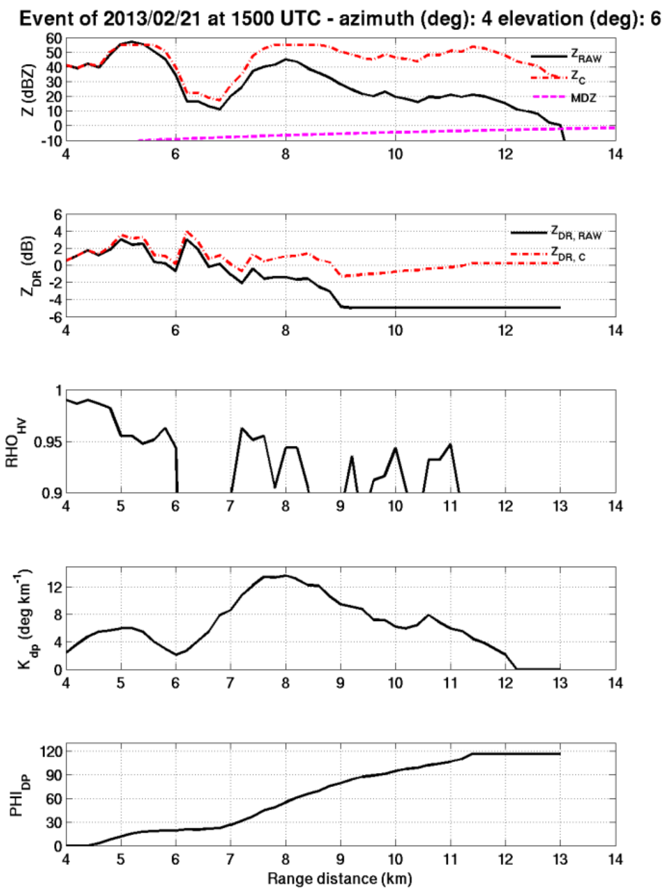

Figure 4:Range profiles of the polarimetric variables Z, Z_{DR}, K_{DP}, ρ_{HV} and Φ_{DP} corresponding to the 4^{th} –deg of azimuth and 6 deg of antenna elevation. The observations refer to event occurred on 21 February 2013 at 1500 UTC.

3.2 Polarimetric rainfall estimation

Figure 5 shows the cumulated rainfall field estimated between 1500 and 1800 UTC on 21 February 2013 using the combined polarimetric algorithm described in Section 2. The peak of the precipitation field retrieved over ground is very close to the radar site. The nearby raingauge, located in Catania at about 6 km from the radar, registered about 60 mm in 1 hour and about 71 in 1 and a half hour. The relative performance of the considered algorithms (i.e. R_Z, R_K, R_C) has quantitatively evaluated in terms of the following scores: ε = <RR - RG>, σ_ε = $[<(RR- RG)^2>]^{1/2}$, Bias = <RR>/<RG>, FSE=RMSE/< RG >, the symbol < > denoting the average operator. The error indicators are summarized in Table 1. They outline, on one side, the improvement obtained through the use of the combined polarimetric algorithm (R_C) with respect to the canonical R-Z relationship either in terms of RMSE (and FSE) or in terms of Bias. On the other side, it can be noticed that R_K outperforms RC in terms of bias although the RMSE is higher due to the larger error standard deviation, i.e., σ_ε.

Table 1: Error scores summarizing the performance of the considered radar rainfall algorithms for the event of 21 February 2013.

	ε	σ_ε	RMSE	FSE	Bias
R_Z	-1.62	2.12	2.65	0.64	0.61
R_K	-0.6	2.64	2.63	0.64	0.91
R_C	-0.81	2.16	2.28	0.55	0.80

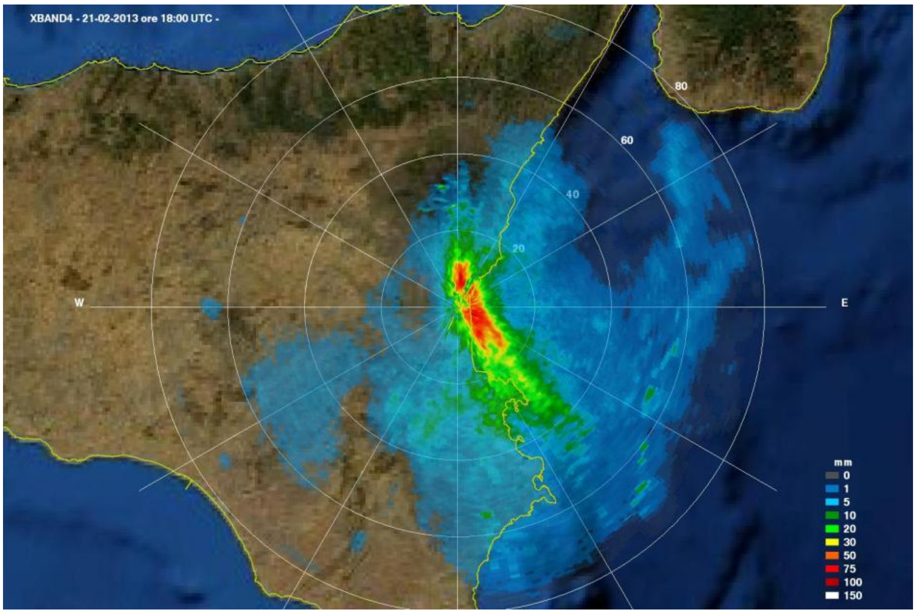

Figure 5:Estimated rainfall cumulated within 15:00 and 18:00 UTC on 21 February 2013.

3.3 Polarimetric signatures of intense convection: the 21 August 2013 case study

On 21 August 2013, a mesoscale convective system, generated around at 0400 UTC by the temperature gradient between sea and land surface, flooded the city of Siracusa (south-eastern Sicily). As for the other considered event, the storm hit only marginally the land, having been developed mainly on sea. The maximum amount of precipitation registered in just two hours by the rain gauge located in Siracusa was about 180 mm. According to the radar observation at vertical incidence angle collected at 0800 UTC, the approximate Freezing Layer Height (FLH) was at about 3.4 km. Figure 6 shows the evolution between 0450 UTC and 0500 UTC in terms of VMI (upper panels). On the eastern direction the effect of signal extinction can noticed. The lower panels show the Probability of Hail Detection, expressed in percentage, as deducted by the relative vertical distance between the 45-dBZ echo top and the FLH (Waldvogel et al., 1979; Holleman, 2001). It is worth mentioning that the reliability of this methodology can be influenced by the relative distance between the storm cell and the radar. For this reason, a low POH might not exclude the hail precipitation.

According to the POH calculated at 0450 UTC, a high probability of hail at about 20 km from the radar could be responsible for the strong attenuation that culminated with the signal extinction which amplified ten minutes later.

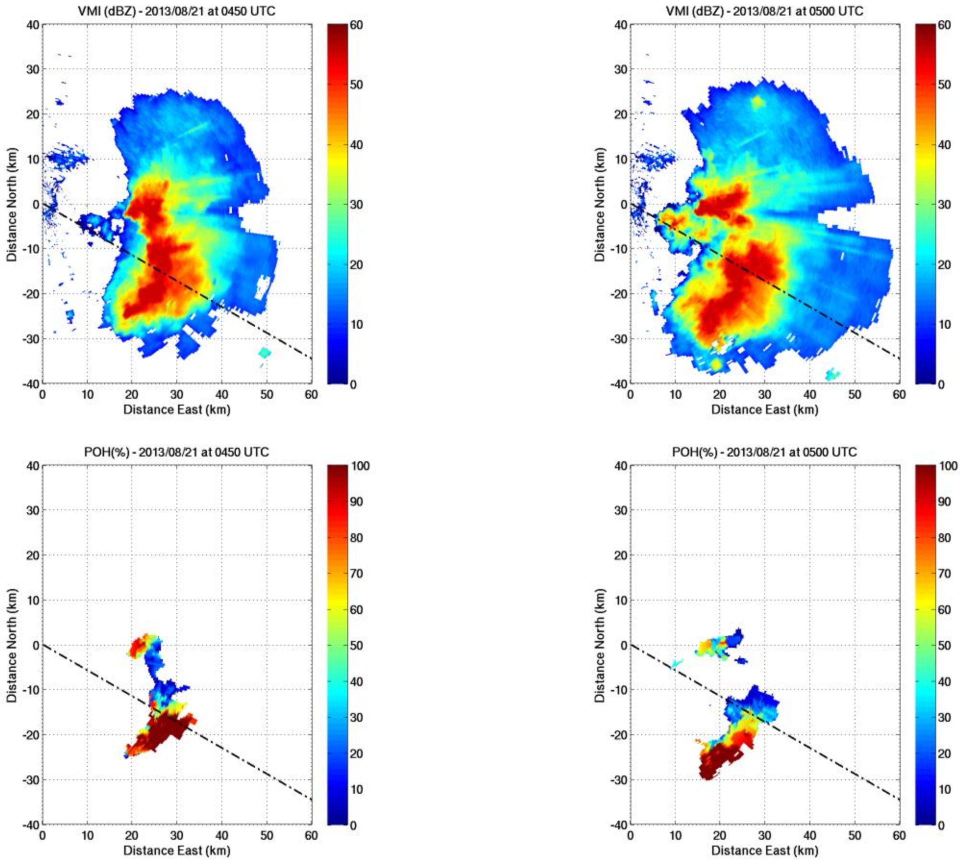

Figure 6: Vertical Maximum Intensity (VMI) displaying the supercell observed between 0450 UTC (*upper left panel*) *and 0500 UTC* (*upper right panel*) *on the 21 of August 2013. The bottom panels show the corresponding Probability of Hail* (*POH*) *maps. The dash dotted line identifies direction of RHIs shown in Figure 7.*

From Figure 7, showing the pseudo RHIs taken at the 121th-deg of azimuth, we may notice that the cloud top altitude reached a 12 km height. The high reflectivity core (*Z* higher than 45 dBZ) exceeded the altitude of 10 km. Interestingly, the so-called Z_{DR} column may be noticed at about 30 km from the radar, where Z_{DR} values higher than 1 dB can be found up to about 5 km of altitude, that is about 1.5 km above the presumed FLH. Additionally positive values of K_{DP} can be found up to the same altitude. Correspondingly, the correlation coefficient drops to about 0.85. These polarimetric signatures are compatible with super cooled raindrops coexisting with hail as it typically happen during the mature phase of a thunderstorm. Starting from about 30 km from the radar, the high core of Z, Z_{DR} and K_{DP} with associated depression of ρ_{HV} below the FLH is compatible with rain and hail mixture.

4 Conclusions

This work has documented the analysis of two severe convective storms observed in Southern Italy by an operational dual-polarization X-band radar operating inside the Catania airport. Both the considered meteorological events determined the localized but remarkable ground effects. The polarimetric radar data have outlined the likely presence of hail, as confirmed by standard methodologies employing reflectivity only and press reports. Although quantitative analysis of such intense, hail-bearing events using data from X-band radar is still a challenging task, especially as far as attenuation correction is concerned, results of classification highlighted to capability of capture meteorologically relevant processes while the combined polarimetric rainfall algorithm has shown the capability to well reconstruct the surface rainfall field registered by the available rain gauges.

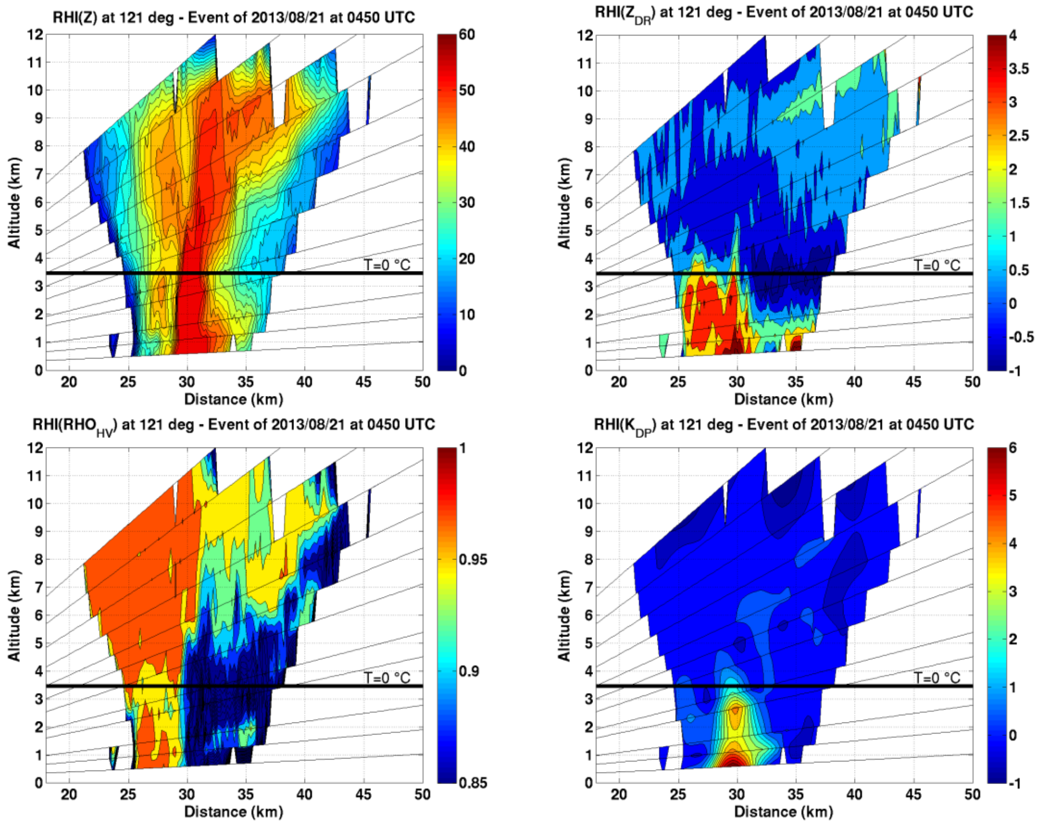

Figure 7: Pseudo RHIs taken at 121-deg azimuth of polarimetric variables observed on 21 August 2013 at 0450 UTC. The horizontal line shows the approximate height of the Freezing Layer as retrieved by vertical radar observations at 0800 UTC.

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