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Which hydrometeor classification scheme is realistic using ZH, ZDR and temperature in complex orography? A study based on operational C-band polarimetric weather radar in northern Italy

R. Cremonini[1], **R. Bechini**[1], **P. P. Alberoni**[1], **and M. Celano**[2,3]

[1]ARPA Piemonte – Area delle attività regionali per l'indirizzo e il coordinamento in materia di previsione e monitoraggio ambientale, Torino, Italy
[2]ARPA Emilia-Romagna - Servizio IdroMeteorologico, Bologna, Italy
[3]Università di Ferrara - Dipartimento di Fisica, Ferrara, Italy

Abstract. Hydrometeor classification is a challenge with important applications for operational monitoring, diagnosis of meteorological phenomena and potential impact in the interaction with limited area models.

Most known studies applied to severe weather conditions are based on research radar with full polarimetric capabilities, considering algorithms that combine ZH, ZDR, KDP, ρ, LDR and T from radiosounding, model or climatology. However it has been shown that for many hydrometeor types, the most discriminating variables are ZH, ZDR and T.

The radar considered in this study are operational C-band systems located in the Po valley, with klystron transmitter, but the hardware, the scan strategies and the installations are different. Moreover, the polarimetric variables available (ZH and ZDR) are only a reduced set with respect to the full set used by other authors.

The possibility to apply such classification scheme, based on fuzzy logic, to operational C-band polarimetric radar in complex orography is investigated. The focus is on the definition of how many and which hydrometeor types can be realistically identified in this particular conditions.

1 Introduction

With the aim to investigate the reliability of hydrometeor classification schemes based on radar measurements, two polarimetric C-band systems located in Northern Italy are considered: the San Pietro Capofiume GPM-500C radar (SPC hereafter), managed by ARPA Emilia-Romagna and located almost at sea level near Bologna; the Monte Settepani GPM-250C radar, managed by ARPA Piemonte, in the Ligurian Apennines at 1400 m height. Both radar have polarimetric capabilities (ZH and ZDR), with alternate horizontal and vertical polarization using a fast ferrite switch. The main differences among the two systems are the antenna: central feed with radome for Settepani, dual offset without radome for SPC; and the receiver: full digital for Settepani, analog with AGC for SPC.

Both systems perform volume scans, although with different parameters (Table 1), and operate in a complex orography environment. This makes an algorithm for particle identification extremely useful in winter season, in order to distinguish between rain and snow precipitation. On the other side, during summer season, the frequency and severity of storms and hailstorms claims for a procedure to identify the type of precipitation associated with such phenomena. Finally, the 3-dimensionality of the radar hydrometeor classification should be soon exploitable in the interaction with limited area model.

2 Particle Identification algorithms

2.1 Algorithm 1

The classification algorithm implemented for the SPC radar belongs to the fuzzy logic family and refers to the scheme developed at the NSSL (Zrnic at al., 2001), but with a reduced set of polarimetric variables. The scheme is based on a combination of weighting functions associated with a particular hydrometeor class. These are trapezoidal functions and the arguments are the horizontal reflectivity ZH and the differential reflectivity ZDR that present the strongest discriminating power for the classification. In analogy with the probability density functions, the membership functions are the product of a 1-dimensional weighting function for ZH (Wj(ZH)) with a conditional weighting function for ZDR (Wj(ZDR|ZH)) and they decrease linearly with distance from 1 to 0 in the "fuzzy boundaries". The two-dimensional polarimetric membership functions over the space ZH-ZDR are presented by Straka et al. (2000) and they are shown in Fig. 1.

Correspondence to: R. Bechini
(Renzo.Bechini@csi.it)

Table 1. Monte Settepani andS. Pietro Capofiume system specifications.

Main technical data of the radar system		
	Settepani	**S.Pietro**
Radar type	GPM 250C	GPM 500C
Polarization type	Linear H and V	Linear H or V
Antenna type	Central feed	Dual offset
Antenna diameter	4.2 m	5 m
Beam width	1.0 deg max. w/o radome	0.9 deg
Maximum sidelobe level	−28 dB	−30 dB
Maximum cross polar discrimination	−25 dB	−27 dB
Antenna gain	44.5 dB	46 dB
Radome type	Sandwich	/
Radome transmission loss	0.2 dB max., one way	/
Transmitter type	Klystron	Klystron
Frequency	5600÷5650 MHz	5430÷5640 MHz
Peak Power	≥ 250 kW	500 kW
Pulse length	0.5, 1.5, 3.0 μs	0.5, 1.5, 3.0 μs
PRF	300÷1200 Hz	300÷1200 Hz

Polarimetric scan parameters	
Settepani	**S.Pietro**
11 elevations, from −0.3 deg to 28.5 deg.	15 elevations, from 0.5 deg to 18 deg.
H-H-V transmitting mode, 120 integrated pulses.	H-H-V transmitting mode.
Pulse width=0.5 μs, PRF=1100 Hz.	Pulse width=0.5 μs, PRF=1200 Hz.
Range resolution=300 m, repetition time=10'	Range resolution=250 m, repetition time=15'

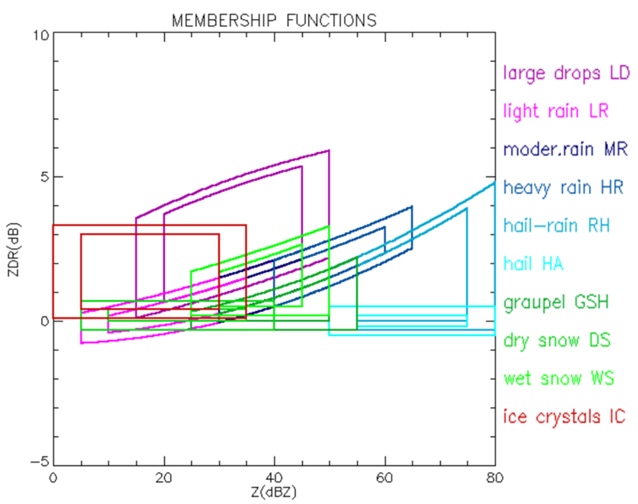

Fig. 1. Radar membership functions for Algorithm 1.

The (environmental) temperature is the other parameter used for the classification and it helps to distinguish between hydrometeor types by removing some ambiguities. The algorithm uses a standard atmospheric profile of 6.5° Km^{-1} starting from the surface temperature measured by ground local stations.

The algorithm can be expressed as:

$$\mathrm{Sj} = (\mathrm{Wj(ZDR, ZH)Wpol} + \mathrm{Wj(T)WT})/(\mathrm{Wpol} + \mathrm{WT}) \quad (1)$$

where j is the j-th hydrometeor class, Sj is the threshold value, Wj(ZDR,ZH) is the polarimetric membership function, Wj(T) is the temperature membership function, and Wpol, WT are multiplicative factors (less or equal to 1) that define the relative importance of each variable.

The assignment is accomplished by taking the highest value of the combination of weighting function, thus each image pixel is associated to the hydrometeor class that maximizes the threshold Sj. Wpol, WT and Sj are important parameters and they have to be calibrated to obtain a correct microphysical classification that presents both a polarimetric and a thermal characterization. In this work, the multiplicative factors are set to 1 and the minimum acceptable threshold is 0.55.

Ten hydrometeor classes can be discriminated by this scheme: light rain LR (<5 mm h^{-1}), moderate rain MR (5–30 mm h^{-1}), heavy rain HR (>30 mm h^{-1}), large drops LD, rain-hail mixture RH, graupel-small hail GSH, hail HA, dry snow DS, wet snow WS and ice crystals IC.

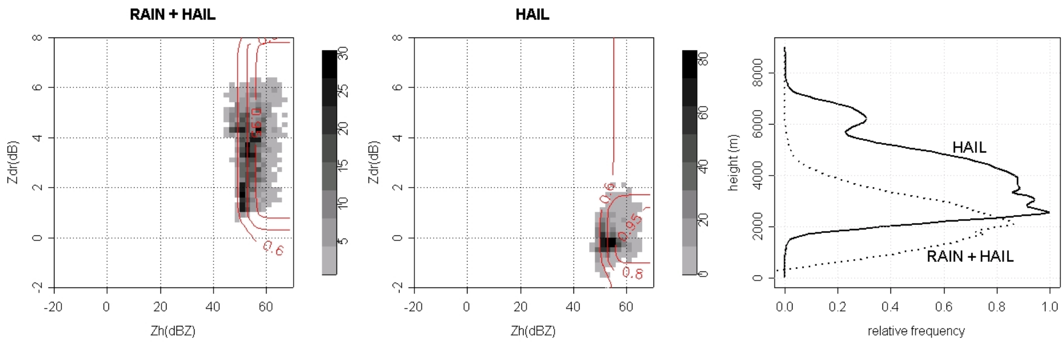

Fig. 2. Left and middle: contours of radar membership functions for rain+hail and hail (Algorithm 2) with Settepani ZH, ZDR pairs densities over the whole polar volume for the 31-07-2003 event. Right: distribution with height of rain+hail and hail observations.

2.2 Algorithm 2

This algorithm, mainly based on the work of Liu and Chandrasekar (2000), is being tested operationally on the Monte Settepani radar data. The beta function is used as the form of the radar and temperature membership functions (MBF), but here the inference rule is not the product of all the MBF: the total probability (P_T) for each hydrometeor type is given by the product of the temperature MBF and the weighted sum of the ZH and ZDR MBF:

$$P_T = MBF(T) * \sum_i^N [w(x_i) * MBF(x_i)] \Big/ \sum_i^N w(x_i) \quad (2)$$

where N=2, x_1=ZH and x_2=ZDR, $w(x_i)$ are the weights associated with each radar parameter and T is the temperature measured by sounding. This is motivated by the need to mitigate the effect of measurement errors, especially on ZDR, which may show unreliable values mainly due to partial beam filling or side lobes effects. For the same reason ZDR is averaged over a 3 beams×3 range gates window in the polar volume. When the total probability is below 0.5, the radar cell is considered not classified. The hydrometeor classes are: large drops, drizzle, rain, heavy rain, hail mixed with rain, hail, graupel, wet snow, dry snow, crystals. A peculiarity of this implementation is that the clutter is treated exactly as an additional hydrometeor type and is identified within the same fuzzy logic volume processing, allowing a reduced total computation time. In this case 3 additional radar parameters are considered: spatial variance of ZDR, Doppler velocity, difference between actual and statistical clear sky reflectivity values, giving N=5 in Eq. (2), with *MBF(T)*≡1.

Out of the fuzzy scheme, further checks on the vertical gradient of reflectivity, spatial average and variance of Doppler velocity are performed to respectively identify eventual anomalous propagation and second trip echo (typically characterised by high velocity spatial variance and average normally distributed around zero). Finally, an iterative algorithm (Gorgucci and Scarchilli, 1996) is applied in order to identify cells possibly affected by signal attenuation.

The two algorithms implemented for SPC and Settepani use different polarimetric and temperature MBF for the classification (trapezoidal and beta functions respectively, with different parameterisations). In addition, Algorithm 2 ingests the measured temperature profile by sounding, whereas Algorithm 1 uses a standard atmospheric profile.

3 Case studies

In order to evaluate the performance of the classification algorithms several case studies have been considered, both stratiform and convective.

On July, 31 2003 a cold front was moving South-Eastward over North-Western Italy, inducing a zero level decrease from 3650 m at 00 UTC to 3200 m at 12 UTC, and originating deep convection especially over sea during the morning. The hydrometeor classification based on the observations of the Settepani radar highlights an area of hail mixed with rain in the lowest layer below the main storm cell, surmounted by dry hail between approximately 2000 and 7000 m height (Fig. 2). On the upwind side of the storm, below the reflectivity overhang, a column of large drops is evidenced when the sounding at 00 UTC is used in the algorithm, in good agreement with other observational studies of similar hail storms (Hubbert et al., 1998). If instead the sounding at 12 UTC is considered, part of the large drops and drizzle are identified as wet snow. Over land the precipitation is less severe, with rain and heavy rain surmounted by graupel/dry snow. Due to extremely intense precipitation, part of the downwind side of the storm is marked as possibly affected by attenuation up to the medium troposphere. The overall classification appears reasonable, although the sensitivity to the temperature profile given by the multiplicative MBF (Eq. 2) is quite relevant, especially for the pairs rain/graupel and large drops/wet snow.

On March, 7 2004, a conspicuous snowfall interested the area explored by the SPC radar. This event has been selected as representative event for a stratiform precipitation. The presence of a bright band phenomena is clearly highlighted in the PPI shown in Fig. 3a, b. In spite of this radar observation, the Borgo Panigale (Bo) synoptic station (roughly

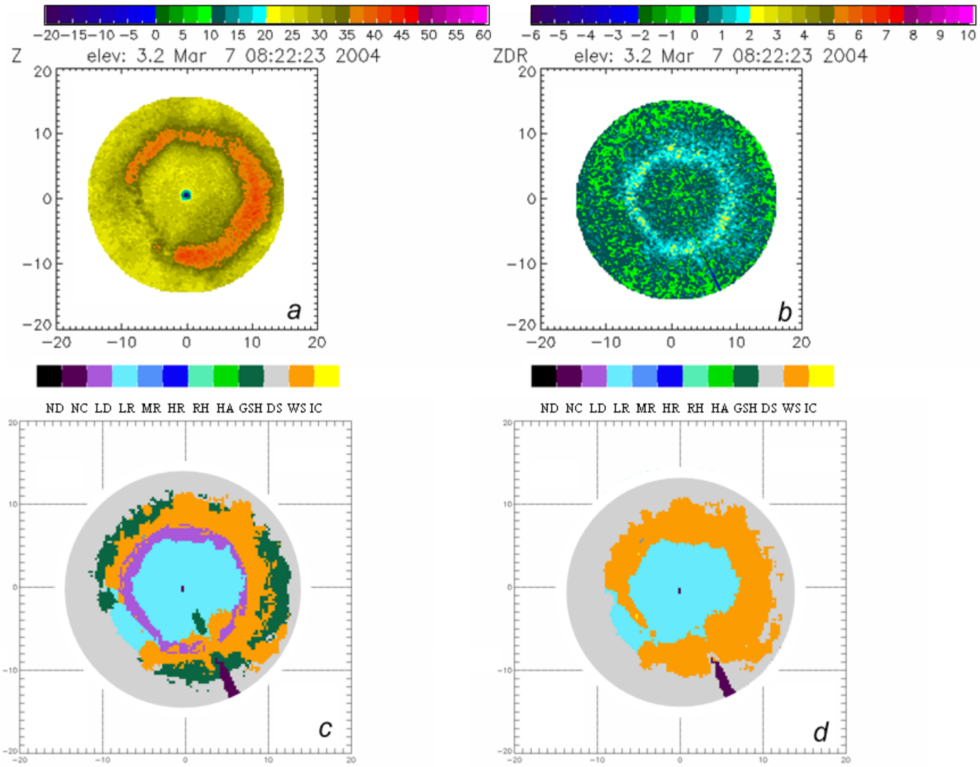

Fig. 3. Stratiform event of 07-03-2004. Three degree elevation ppi of (a) horizontal reflectivity ZH, (b) differential reflectivity ZDR, (c) SPC hydrometeor classification, (d) SPC hydrometeor classification, considering the second identified class for graupel and large drops.

20 km south of the radar) report the presence of snow during the whole day, even if the surface temperature measured by Saiarino station (roughly 10 km south-east of the radar site) indicated a big variability of temperature ranging from 0 to 5°C during the day (at 8.22, time of data shown in Fig. 3, the temperature is 2.8°C). It is possible that the region around the radar was interested by a rain-snow mixture event at the lowest layers or by a double bright band event, with a second bright band closer the ground. A direct application of the SPC scheme is shown in Fig. 3c, where the classification indicates the presence of light rain in the area close the ground, wet snow in the melting layer region and dry snow in the region above the bright band. The reader should note the presence of graupel and large drops near the bright band, which is completely unrealistic for a stratiform event. The reason of this misclassification is due to the relative weight of temperature field in the classification algorithm, further the limited set of radar variables used causes that for some hydrometeor classes the output of the classification algorithm is not able to define a single suitable hydrometeor class. This is exact the case which occur in proximity of the bight band level. In this particular situation those pixels classified by the algorithm as graupel are indeed wet snow in the inner edge or dry snow in the outer edge for the region misclassified. Similarly the LD area is mainly re-classified as wet snow. The result of this reclassification is shown in Fig. 3d. These hydrometeors are much more realistic for a stratiform event.

Similar results are obtained using algorithm 2. In particular the bright band is well detected and mainly filled with wet snow, which is found in relevant quantity down to ground level (Fig. 4, left panel), in fair agreement with local observations. Nevertheless an excess of graupel particles is evidenced and a number of large drops are found scattered within the melting layer. Analysing the second identified particles, the overall good "isolation" of wet snow is confirmed, since the most frequent second choices (graupel and large drops) have average probability about 15% lower respect to wet snow. On the other side for the large drops identification, the dominant second choice is wet snow, with just a 6% lower probability (Fig. 4, middle panel), confirming the idea of a possible misclassification. For comparison the same statistics for the convective case is shown in the right panel of Fig. 4, where the higher likelihood of this classification is clear, since the second choices are physically nearest (drizzle and rain) and their average probabilities are considerable lower (>20% difference).

4 Conclusions

A preliminary performance analysis has been conducted on two different algorithms for hydrometeor classification, both based on fuzzy logic, using radar data from the polarimetric systems of San Pietro Capofiume and Monte Settepani, in Northern Italy. The available polarimetric parameters are

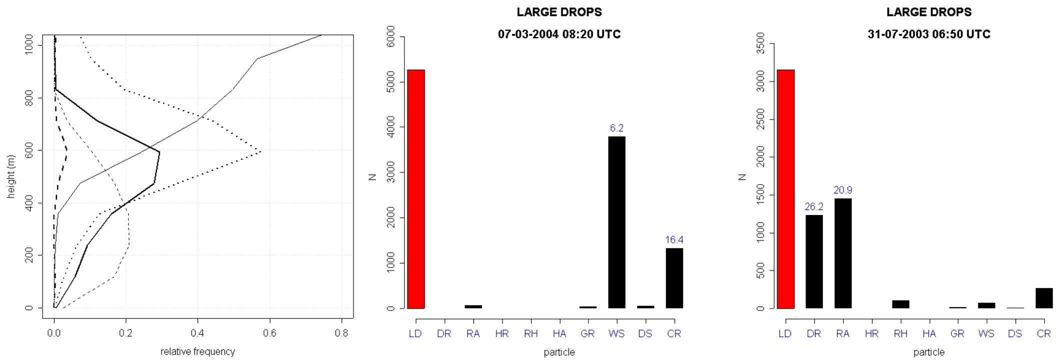

Fig. 4. Left: distribution with height of wet snow (solid thick line), dry snow (solid thin), graupel (dotted thick), large drops (dashed thick), rain (dashed thin) for SPC classification of 07-03-2004 stratiform event. Middle and right: distribution of the second identified particles when the first identification is large drops: the numbers above the bars indicate the average minor probability.

ZH and ZDR, a reduced set with respect to other polarimetric radar used in similar studies. The aim was to asses the significance of such classification in this context, for summer and winter meteorological conditions. Although for convective events the full set of particles considered (drizzle/light rain, rain, rain + hail, hail, large drops, graupel, wet snow, dry snow, crystals) appears a reasonable choice despite the lack of further polarimetric information, in stratiform cases this set should be a priori reduced, since the algorithms are not able to leave out of consideration not physically consistent particles, such as large drops and graupel, which are easily identified instead of wet snow, rain and dry snow. A key role in the classification process is played by the temperature profile, which is needed to resolve several ambiguities. Using a standard atmosphere profile, based on ground temperature as in Algorithm 1, has the advantage of a good temporal resolution, but may be misleading in cases with temperature inversions, frequent in winter season and highly depending on the orographic environment. On the other hand, using the observed sounding profile provides high vertical resolution but may often be too old, respect to actual radar observations. A third approach that will be investigated is the use of model forecasted temperature profiles at different locations, in order to increase both time and space matching with radar observations.

Finally, an analysis of the second identified particles and their minor probability with respect to the first identification has been done, providing information about the classification strength: use of this information, together with some spatial contiguity and physical constraints will be investigated in order to refine the classification scheme.

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