Hail detection and quantification with C-band polarimetric radars: results from a two-year objective comparison against hailpads in the south of France

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1. Introduction

Among the various meteorological risks, hail is certainly one of the least understood, measured and forecasted. This is in part due to the extremely high space-time variability of the phenomenon as well as to the complexity of the microphysical and kinematical processes that are involved. In contrast with that, the economic consequences of hail storms can be devastating in sectors like agriculture, aviation, car manufacturing, etc.

Because of their ability to monitor the 3D structure of storms at very high space-time resolutions (>5 minutes and >1 km²), radars have been long recognized as a valid tool to detect and quantify hail. Early approaches relied either on reflectivity thresholds (55 dBZ or so), Donaldson (1959), applied to PPIs or pseudo-CAPPI, or on 3D-derived information such as echo tops, Vertically Integrated Liquid Water (VIL), Amburn and Wolf (1997), or the height difference between the 45 dBZ isopleth and the freezing level. The latter, often referred to as the Probability Of Hail (POH), Waldvogel et al. (1979), Delobbe and Holleman (2006), is supposed to be the best candidate among all conventional algorithms. Most operational radar services have introduced conventional algorithms for hail detection.

The advent of polarimetry into operational networks opens new perspectives. Polarimetry allows better distinction between meteorological and non-meteorological targets (e.g. ground-clutter). Secondly, polarimetry (and specifically the differential phase $\Phi_{DP}$) offers a mean to correct if not all a significant fraction of the precipitation-induced attenuation, which is quite frequent in hail-bearing convective systems. Finally, the availability of additional parameters (differential reflectivity $Z_{DR}$, correlation coefficient $\rho_{HV}$ and specific differential phase $K_{DP}$) allows improving the distinction between heavy rain, dry hail and wet, melting hail and the estimation of its size or its kinetic energy.

Many works have been conducted and published with S band radar to define the polarimetric signature of hail according to $Z_{H}$, $Z_{DR}$, $\rho_{HV}$ and $\Phi_{DP}$ values. Membership functions have been established and computed in a fuzzy logic approach to identify hail among other hydrometeors. Nevertheless, several studies have reported on the many different habits and fall modes of hail in convective precipitations:

- Dry, spherical or not spherical but tumbling hailstones (close to zero $Z_{DR}$)
- Melting hailstones with a solid ice core covered by a torus of water stabilized on a horizontal axis (positive $Z_{DR}$);
- Large, dry, oblate hailstones falling with their major axis along the vertical (negative $Z_{DR}$).

This clearly makes the determination of the membership functions quite complicated in order to keep a high probability of detection POD and a low false alarm rate FAR. Moreover, at C-band the classification of hail is further compromised because hail may have a size comparable to the radar wavelength and therefore Mie scattering must be considered. Furthermore, recent works pointed out, Tabary et al. (2009), that C-band radars face a stronger attenuation in hail-bearing cells than that of S band radar. Attenuation affects downstream $Z_{H}$ and $Z_{DR}$ values but studies have shown that it can also affect $\rho_{HV}$ and $K_{DP}$ values. Indeed, another problem related to polarimetric radar echoes interpretation is the effect of large azimuthal variations of $Z_{H}$ within the radar resolution volume. Ryzhkov and Zrnic (1996) explained that negative bias on $K_{DP}$ and $\rho_{HV}$ were observed in such situations.
This problem, which can affect S band observations of leading edges of squall lines for example, is certainly more acute in C band observations due to a stronger sensitivity to attenuation. Thus, an upstream heavy rainfall can mask one part of the radar measure volume downstream, causing strong azimuthal reflectivity variations in this one, and thus more frequent K\text{DP} and ρ\text{HV} negative biases.

The goal of this study is two fold: Rigorously assess the performance of the current C-band fuzzy logic hydrometeor classification algorithm implemented in Meteo France, which is based on that by Marzano et al. (2006) and determine the polarimetric signature of hail and no-hail measurements in view of a future modification of the membership functions.

2. Data set

The present study has been conducted using data from the C-band polarimetric weather radar located in Toulouse, SW of France. This radar provides high-resolution (0.5°x240m) polarimetric data at 12 different tilts. The standard revisit time of the lower angles of elevation (0.8°, 1.5° and 2.5°) is 5 minutes. As described by Boumahmoud et al. (2010), all of these data are pre-processed (ground-clutter identification, Z\text{H} and Z\text{DR} calibration, Φ\text{DP} offset removal and filtering, K\text{DP} estimation, correction of attenuation using Φ\text{DP} values…) and injected into fuzzy-logic classification algorithm considering membership functions of several hydrometeors. The “dry hail” and “wet hail” identifications are extracted from this processing chain every 5 minutes and gathered to get “hail imprints” allowing to display radar hail traces of each event. The current membership functions for hail do not consider hail size.

ANELFA, a farmers association, operates an extensive network of hailpads in the south west of France in order to monitor the damages caused at agriculture. More information on the characteristics of the hailpads and the extension of the network can be found in Tabary et al. (2009). It is sufficient here to mention that hailpads record the starting time and duration of the event as well as the event accumulated hailstone size distribution (above 5 mm diameter) and the hail kinetic energy, mass, etc. The position of the hailpads is determined by GPS. The hailpads are rigorously checked and thus they can be used to validate the performance of the hail identification algorithms in an analogous way as rain gauges control the quality of precipitation quantification estimators.

The study considers 6 days of hailstorms during the “warm seasons” of 2008 and 2009. The area of study has been reduced to 80 km around the Toulouse radar, where 220 hailpads are present, to limit representativity errors due to the beam being several hundred meters above the surface. In general terms, the lower elevation angle of 0.8° is used to be closer to the ground but if it is affected by ground clutter, higher tilts such as 1.5° or even 2.5° are used.

3. Hail identification algorithm performance

The performance of fuzzy logic identification based on polarimetric variables has been evaluated using the pads. It has also been compared to that of the Z\text{H}>55 dBZ method with and without attenuation correction to evaluate whether polarimetry offers any advantage regarding hail identification. Table 1 summarizes the results.

<table>
<thead>
<tr>
<th>Method</th>
<th>POD</th>
<th>FAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z\text{H}&gt;55 dBZ</td>
<td>66.2 %</td>
<td>48.9 %</td>
</tr>
<tr>
<td>Z\text{H}\text{CORR}&gt;55 dBZ</td>
<td>88.7 %</td>
<td>67.8 %</td>
</tr>
<tr>
<td>Dry + wet hail</td>
<td>90.8 %</td>
<td>67.6 %</td>
</tr>
<tr>
<td>Dry hail</td>
<td>71 %</td>
<td>43.9 %</td>
</tr>
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</table>

The correction of attenuation allows to reach a higher POD but higher FAR too. The results of the fuzzy logic classification show that the scores are slightly better than those of the Z\text{H}\text{CORR} method. Advection effects may also have an impact on these results. The strongest example is the situation of the 25\textsuperscript{th} of May, 2009 where fast moving hail-bearing cells have been detected. Fig. 1 shows the “dry + wet hail” imprint without and with advection effects correction. The performances symbols allow to clearly see the increase of POD which quantitatively rises by 25 points of percentage on that particular day.
4. Polarimetric signature characteristics over impacted and non-impacted hailpads

In view of the results of the evaluation it seems evident that the current membership functions need to be revisited. A scheme has been developed to empirically determine the characteristics of the polarimetric variables when hailpads where impacted and try to distinguish them from those where no hail impact was detected but reflectivity was above 45 dBZ. In order to account for the uncertainty due to advection and falling time, and the uncertainty in the duration of hail storms recorded by the hailpads a neighbourhood of 10x10 km around the impacted hailpads and a time interval of +/- 15’ have been explored. Fig. 2 shows the interest of such a procedure. If values are just extracted at the exact vertical of the hailpad at $T_0$ recorded by the hailpad, then no hail values will be extracted from it.

To minimize the impact of phenomena typically affecting C-band measurements only data with low attenuation ($\Phi_{DP} < 30^\circ$) and low azimuthal reflectivity variations ($<10$dBZ/$^\circ$) have been considered. The dataset also includes measurements of the freezing level (provided by models) and the altitude of the beam.

Fig. 3 to 5 show the scatter plot of 150 “hail” and 200 “no hail” polarimetric signatures gathered by this approach. The results are plotted against the projection of the current membership functions profiles (including the borders) of “heavy rain”, “wet hail=rain” and “dry hail” currently considered in the fuzzy logic classification of Météo France. It should be noticed the presence of very high values of $Z_{DR}$, most probably due to resonant effects, and negative $K_{DP}$ due to the influence of the backscatter co-polar differential phase. These scatter plots show a clear distinction between heavy rain and hail, although some overlaps exist. These overlaps could be due to melting hail, but $K_{DP}$ and temperature evolutions analyses showed that some overlapping points remained unexplained by this theory.

These scatter plots suggest that the current membership functions should be redesigned. In particular, the high FAR may be explained by the “wet hail” membership function extending over values where mostly heavy rain was present.

![FIG. 2. ZH images in a 10x10km box around the hailpad (white square in the middle) from $T_0-15'$ to $T_0+15'$ every 5’ with $T_0$ the time of the hail impact recorded by the hailpad.](image)

![FIG. 3. Scatter plot of $K_{DP}=f(Z_{Hcorr})$ for Hail and No hail $Z_{Hcorr}>45$ dBZ (heavy rain) against current membership functions profiles](image)
We have also analysed the vertical profiles of the polarimetric variables in order to determine whether their variation can be related to the severity of hail impacts on the ground. The reconstruction of the vertical profile has been performed taking into account the advection field and the delay between measurements at each elevation. Nevertheless the profiles are a bit noisy, possibly due to errors in the estimation of the advection and the fact that the radar is not extremely volumetric. However, as it can be seen in the example shown in Fig. 6, in some instances it is possible to establish a fairly good distinction between weak hail and severe hail. $Z_{\text{DR}}$ and $K_{\text{DP}}$ vertical profiles are particularly useful, especially when hail crosses the freezing level. If medium hail is hard to identify, weak and severe hail are easily distinguishable. Indeed, when weak hail crosses the freezing level, $Z_{\text{DR}}$ and $K_{\text{DP}}$ values highly increase because the melting is important and fast for that kind of hail. On the contrary, severe hail is not disturbed at all by the crossing of the freezing level, because of high fall velocity and, consequently, low presence time below the freezing level before reaching the ground. Nevertheless deviations in the behaviour of the $Z_{\text{DR}}$ profile have been observed, suggesting that the $Z_{\text{DR}}$ signature of large hail may depend on the melting speed of it.
FIG. 6. Vertical profiles in hail-bearing cells for 3 ranges of kinetic energy and maximum hail sizes observed. The $\Phi_{DP}$ vertical profile is plotted to highlight the low attenuation conditions of these 3 profiles. Green dotted lines represent the $0^\circ$ isotherm estimated from a forecasting model.

5. Conclusion

Although it is more difficult than in S band, hail identification with C-band polarimetric radar seems to be possible under certain measurement conditions (low attenuation and low azimuthal variations of reflectivity). Hailpads are a crucial tool for a rigorous evaluation of the performance of the hail identification algorithms, as well as the study of the hail polarimetric signature in an analogous way as rain gauges are used to validate quantitative precipitation estimators.

Although the data set evaluated is too limited to be statistically representative, some trends in the polarimetric signatures of small and large hail and rain have been observed. The method presented opens the possibility to create empirical membership functions that would greatly improve the scores of the current fuzzy logic classification algorithms, in particular reducing the FAR.

References