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AN IMPROVED METHODOLOGY FOR CLASIFYING CONVECTIVE AND STRATIFORM RAIN

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1. INTRODUCTION

One of the main errors affecting the rainfall estimation by weather radar is due to the fact that the radar measures the value of reflectivity at a certain height instead of doing it at the ground level. Usually the correction of this error is realized extrapolating the observations to the ground by supposing that the Vertical Profile of Reflectivity (VPR) agrees a determined shape. From this point of view is very convenient to correctly distinguish between convective and stratiform precipitation since each kind of precipitation shows a different characteristic VPR. A right separation between convective and stratiform rain is also very interesting in relation to other aspects of the Quality Control of radar measurements as ground clutter substitution (for stratiform rain horizontal substitution may be applied but for convective rain vertical substitution may be better) or the conversion Z-R (a different Z-R relationship would be applied for stratiform or convective precipitation).

Here an improved methodology for classifying rain is proposed. This methodology consists of combining the identification of stratiform and convective pixels according to the algorithms by Sánchez-Diezma et al. (2000) and Steiner et al. (1995), and the results of introducing three new discriminatory variables that characterize the vertical development of the precipitation over each pixel. They are the average reflectivity (measured in mm^6/m^3) above the stratiform bright band height, $\overline{Z}_{abb}$, the average reflectivity bellow this height, $\overline{Z}_{bbb}$, and the 30 dBZ ecotop altitude, $h_{top,\,30\,dBZ}$, which is the maximum height where a value of reflectivity greater than or equal to 30 dBZ is placed.

2. FIRST IDENTIFICATION OF CONVECTIVE AND STRATIFORM RAIN

2.1 Identification of convective rain

The algorithm to identify convective pixels, which we call the Convection Identification Algorithm (CIA) is based in the procedure proposed by Steiner et al. (1995) and was implemented by Sánchez-Diezma (2001) for applying it to images registered by the radar of the Spanish Meteorological Institute (INM) in Barcelona. It consists of capturing the strong reflectivity cores that characterize convective cells by detecting high values of reflectivity and high values of the reflectivity gradient in the first PPI radar image.

This identification procedure presents an important limitation: in zones with stratiform rain where the first PPI intercepts a very intense bright band peak, the first PPI shows groups of pixels with high values of reflectivity which are erroneously identified as convective when the Steiner criteria are applied (Figure 1).

2.2 Identification of stratiform rain

As we said, a first identification of stratiform rain is realized similarly to Sánchez-Diezma (1995) although with some differences (we call the correspondent algorithm the Bright Band Identification Algorithm, BBIA). This identification consists of detecting the maximum peak of reflectivity corresponding to the bright band from the VPRs observed above each pixel. Therefore the procedure only could be applied if volume radar scans are available.

In a first step a local maximum is searched in each observed VPR. It is verified that a decrease of 5 dBZ is produced 500 m above and below this maximum. This condition implies that the detected local maximum follows the standard bright band model (Fabry and Zawadzki, 1995). In this way a collection of local maximum heights with bright band characteristics is achieved. The most frequent local maximum height is computed and is considered the estimated bright band height.

Second, the local mean observed VPR is computed for all the image pixels. Then a local maximum is searched around the estimated bright band height for each local mean VPR (inside the interval 500 m above the estimated bright band height and 500 m below). To consider this local maximum as corresponding to the bright band peak it must verify the bright band characteristics in a more accurate way than in the first step. To determine the real bright band characteristics, first the Mean VPR near the radar (between 10 and 20 km), that we call NMVPR, is obtained averaging the VPRs observed at these distances in the pixels not identified as convective when applying the CIA. Next the VPR that would be observed by the radar over the NMVPR at each distance is simulated by convolution of the NMVPR with the radar beam pattern according to the radar equation. Then a local maximum corresponding to the bright band peak is located at each simulated VPR and the reflectivity decrease between this maximum and 500 m above and below is computed (Figure 2). So a value of those simulated decreases is obtained for each distance from the radar (Figure 3).

Finally, the value of these decreases is computed for each local Mean VPR in all the image pixels that are not identified as convective by the CIA. Subtracting the standard deviation of the observed decreases from the decreases obtained by simulation the decreases thresholds at each distance for considering a pixel as stratiform are determined (Figure 3).

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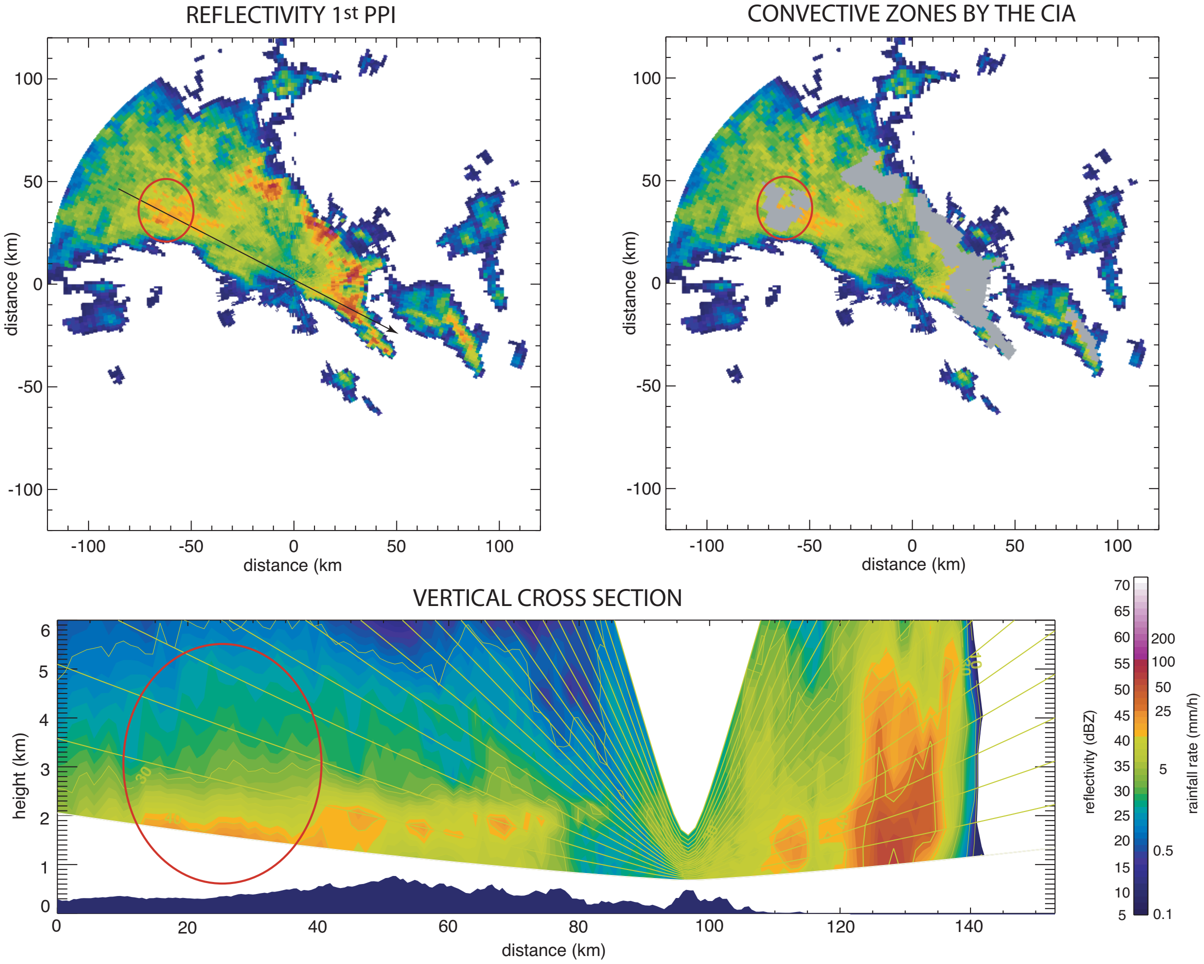

Fig. 1. The convective zones identified by the CIA are showed in the up right figure in grey colour. In this radar image the CIA erroneously identifies as convective pixels the pixels where the first PPI intercepts the bright band (region inside the red contour). In the vertical cross section it is possible to appreciate that in this zone the precipitation is stratiform (notice the bright band).

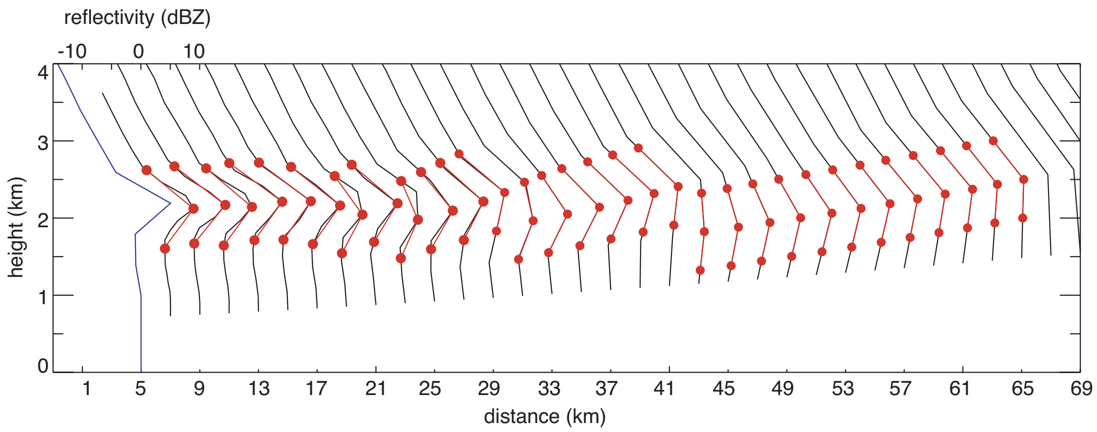

Fig. 2.Simulation of the VPRs the radar would observe over the NMVPR (blue profile). The simulated profiles are plotted in black. The local maximum of each simulated profile related to the bright band and the points 500 m above and 500 m below it are the red circles.

In Figure 4 is showed the result of applying the BBIA. When the first PPI intercepts the bright band or is placed above it, the observed VPRs do not capture the bright band peak and it is not possible to detect the bright band by searching for a local maximum. However for certain distances (while the first PPI is not very high) is possible to search for a strong decrease (here supposed greater than 5 dBZ/km) above the bright band height corresponding to the upper part of the bright band peak (Figures 4b and 4e). In case that the first elevation observation is placed very bellow the bright band maximum the local mean VPR does not show such strong decrease between the first and the second observations and it is searched between the second and the third ones (Figures 4b and 4f).

This gradient criterion is also applied in the pixels where the first elevation is placed bellow the bright band, but the local mean VPR is not able to capture the bright band peak because of the vertical width between the radar observations (Figures 4b and 4d).

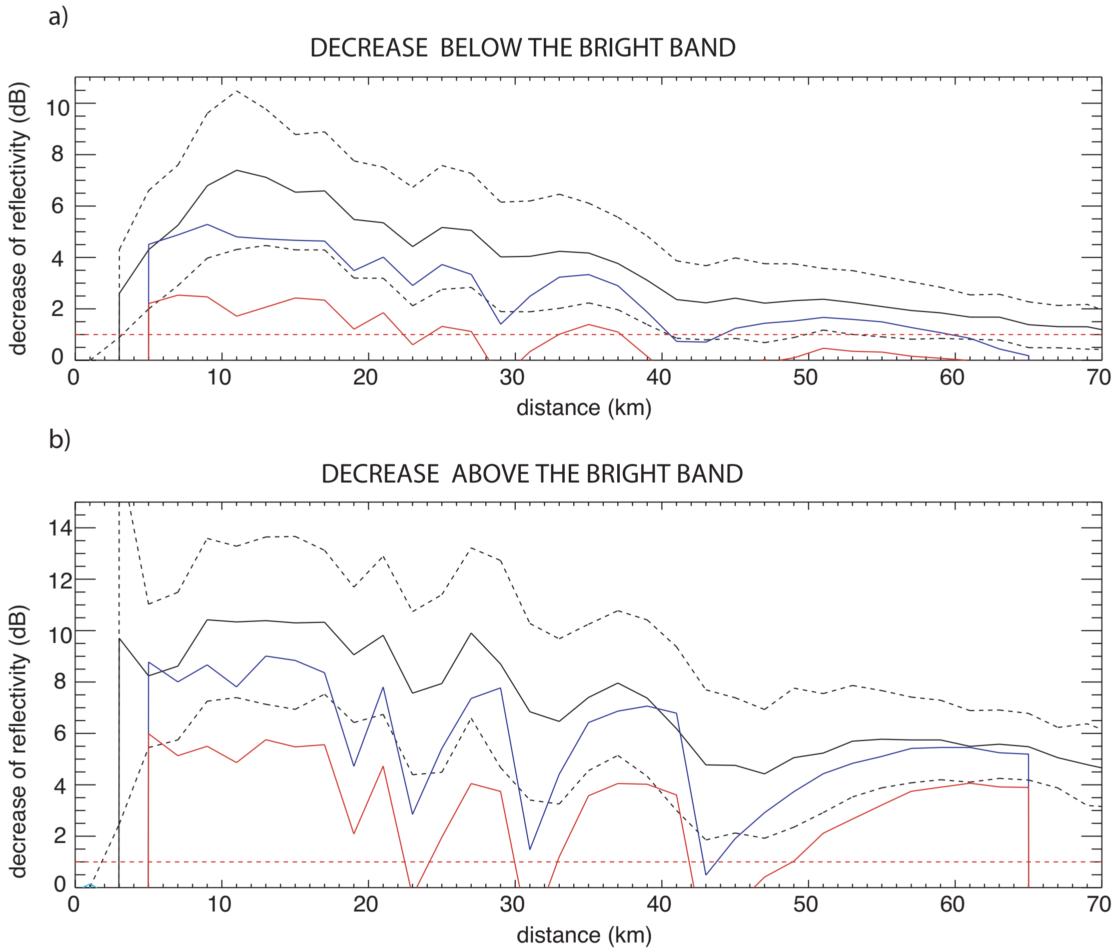

Fig. 3.Obtention of the thresholds for the reflectivity decreases that a maximum of each local Mean VPR must exceed at each distance for considering the corresponding pixel as stratiform. The curves were obtained for one radar image (image in Figure 4). These decreases are computed between the local maximum related to de bright band and the values of reflectivity 500 m below (Figure 3a) and 500 m above this maximum (Figure 3b). In figure the solid black line represents the mean values of the decreases showed by the local mean observed VPRs in all image pixels not identified as convective by the CIA. The black dashed lines represent these mean observed decreases plus and minus the corresponding standard deviation. The blue line represents the decrease obtained from the simulated VPR over the NMVPR. Finally the red line is computed by subtracting the observed standard deviations to the simulated decreases. The values used as thresholds correspond to both red lines except when they are less than 1 dB. Then the threshold is given the value 1dB.

The main limitation of this identification procedure is that it only could be applied for distances where the first PPI is placed below the bright band or is affected by the bright band.

By the other hand the pixels identified according the gradient criterion could also be convective since low convection could also show strong decreases above the bright band.

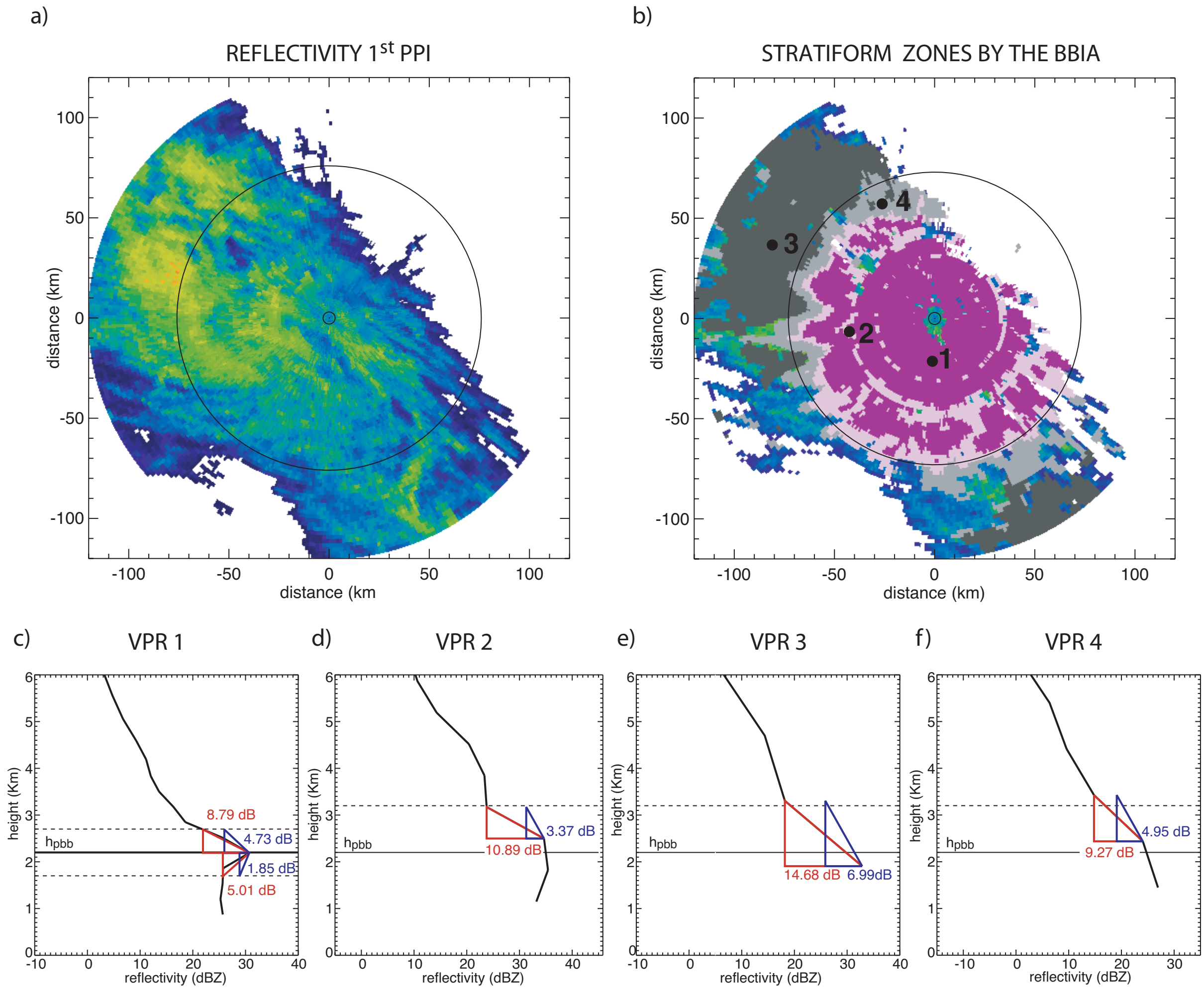

Fig. 4.Result of applying the BBIA to one radar image registered by the radar of the INM (Spanish Meteorological Institute) in Barcelona. The whole precipitation field in this image is stratiform. In Figure 3b the different zones resulting of the bright band identification are showed. The dark violet zones are identified by the peak criterion. The light pink zones are identified by the gradient criterion when they show VPRs with a weak local maximum around the estimated bright band height. The dark grey and the light grey zones are identified by the gradient criterion far enough from the radar for not showing a local maximum around the bright band. The dark grey zones correspond to zones identified by applying the gradient criterion between the first and second elevation measures, and the light grey ones between the second and the third. The circumferences in 4a and 4b correspond to the limit ranges of each criterion. In c), d), e) and f) are showed the local mean observed VPRs at one point in each zone (points 1,2,3,4 in Figure 3b). The blue triangles represent the decrease thresholds and the red ones the decreases showed by the local mean VPRs.

3. INTRODUCING THE AVERAGE REFLECTIVITY ABOVE THE BRIGHT BAND HEIGHT AS A DISCRIMINATORY VARIABLE

Comparing the strong vertical development of convective precipitation against the lower one showed by stratiform rain is tried to be realized by mean of the average reflectivity above the bright band height. To obtain this variable the observed Vertical Profile of Z (reflectivity in function of the height expressed in mm^6/m^3) is integrated from a certain height above the bright band (the height where the radar measures start to not be affected by the bright band) to the top of the precipitation. The result is divided by the integration height interval (Figure 5). Convective VPRs are characterized by high values of reflectivity until they strongly decrease at the ecotop altitude. By the other hand stratiform VPRs show decreasing reflectivity with height above the bright band. According to this, it is expected that convective cells show high values of $\overline{Z}_{abb}$ in comparison to stratiform rain (Figure 5 and Figure 6). The same example showed in Figure 1 is represented in Figure 7. Notice that the zones erroneously identified as convective by the CIA are correctly discriminated by $\overline{Z}_{abb}$.

The problem is that in our region, at the North East of the Iberian Peninsula, on the Mediterranean coast, convective cells sometimes present low vertical development. In these cases $\overline{Z}_{abb}$ shows similar values for convective cells and stratiform rain. A representative example is presented in Figure 8.

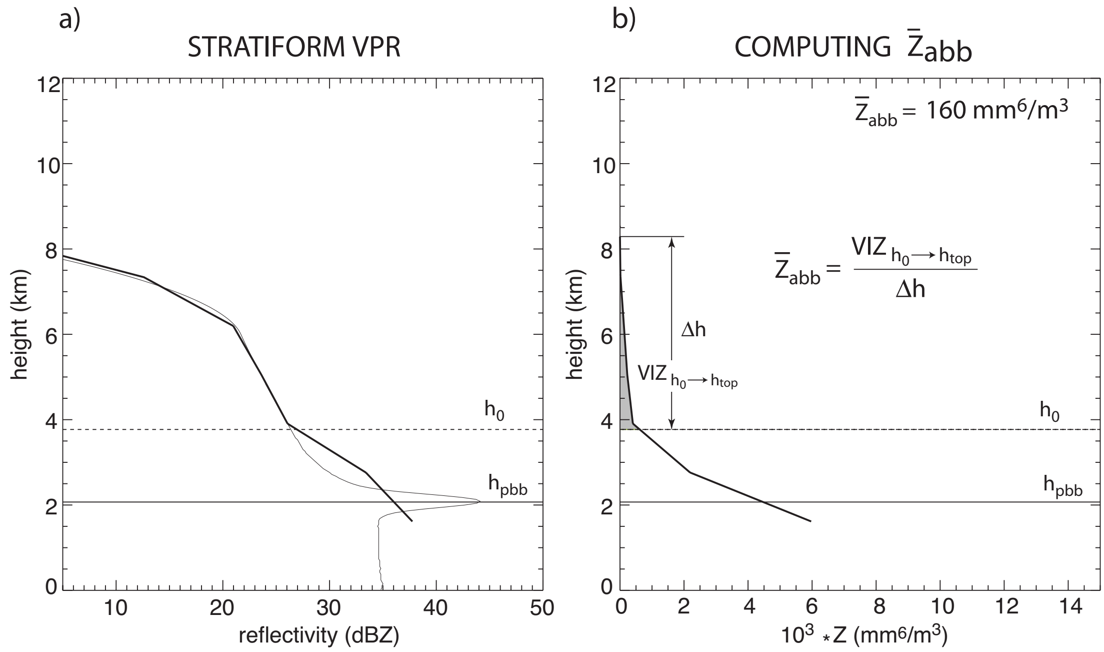

Fig 5.This figure illustrates how $\overline{Z}_{abb}$ is obtained for a stratiform VPR. In a) the observed profile (strong line) that our radar would observe over an original stratiform profile (weak line) is presented. In b) the vertical profile of Z in mm^6/m^3 is showed. The grey area corresponds to the Vertical Integrated Z (VIZ) between a certain height above the bright band and the top of the precipitation. $\overline{Z}_{abb}$ is computed dividing this area by the integrating height interval

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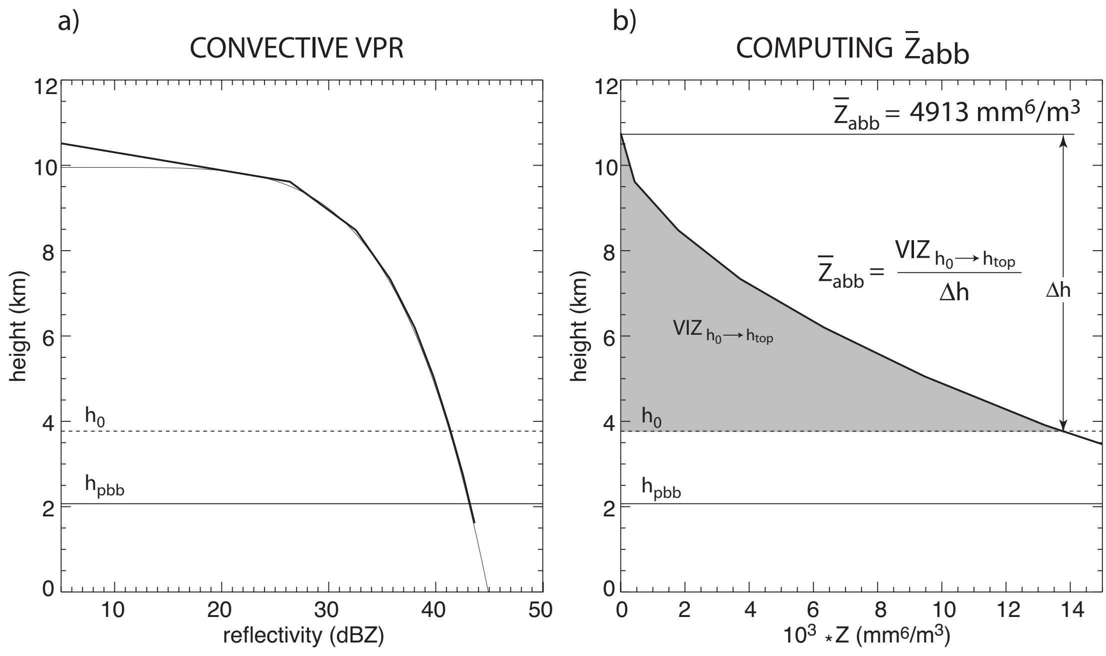

Fig 6.This figure illustrates how $\overline{Z}_{abb}$ is obtained for a convective VPR. In a) the observed profile (strong line) that our radar would observe over an original convective profile (weak line) is presented. In b) the vertical profile of Z in mm^6/m^3 is showed. The grey area corresponds to the Vertical Integrated Z (VIZ) between a certain height above the bright band and the top of the precipitation. $\overline{Z}_{abb}$ is computed dividing this area by the integrating height interval.

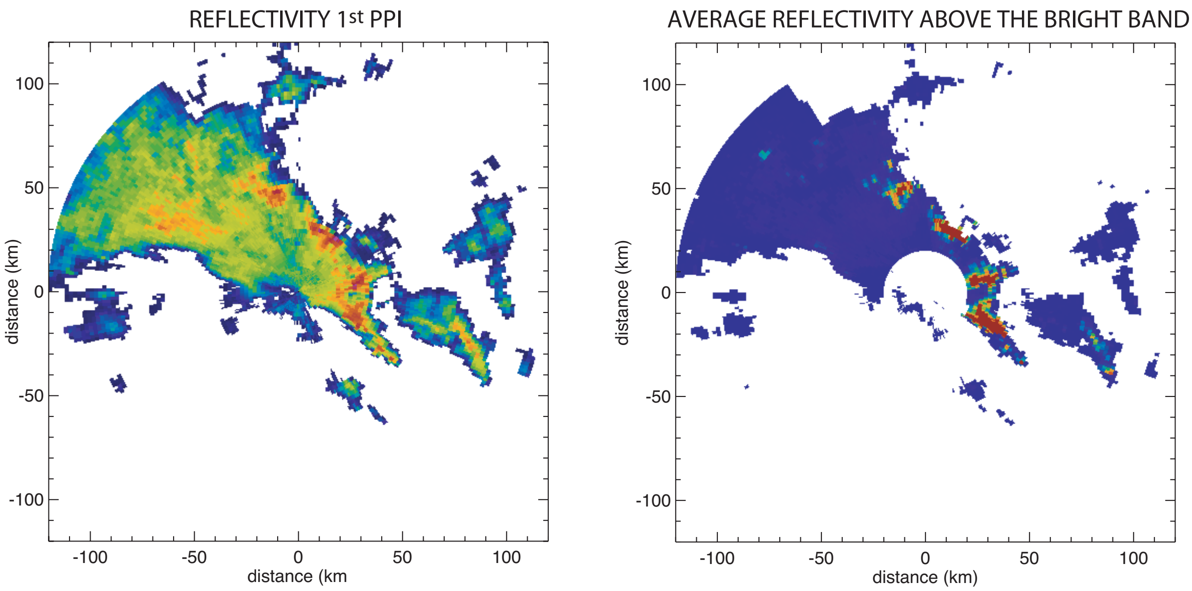

Fig. 7.Representation of the average reflectivity above the bright band, $\overline{Z}_{abb}$, for the same radar image showed in Figure 1. The $\overline{Z}_{abb}$ is represented using a linear scale from cold (low $\overline{Z}_{abb}$) to hot colours (high $\overline{Z}_{abb}$). In this case $\overline{Z}_{abb}$ is able to correctly discriminate convective and stratiform zones (see the vertical cross section in Figure 1).

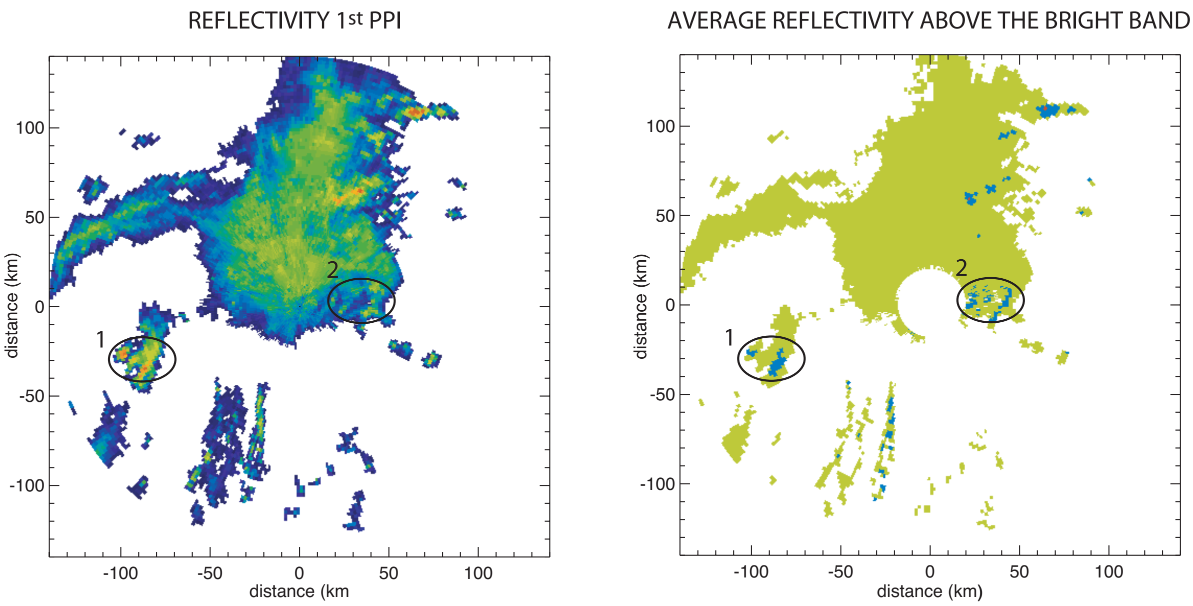

Fig 8.Representation of the average reflectivity above the bright band, $\overline{Z}_{abb}$, for one radar image. The yellow colour indicates low $\overline{Z}_{abb}$ (less than the percentile 99% of the distribution of $\overline{Z}_{abb}$ in pixels identified as stratiform by the peak criterion of the BBIA). The blue colour indicates medium $\overline{Z}_{abb}$ (between the percentile99% and 3000 mm^6/mm^3). The red colour indicates high $\overline{Z}_{abb}$ (greater than or equal to 3000 $mm^6/mm3$). In this case $\overline{Z}_{abb}$ is not able to discriminate between low convection (contour 1) and some stratiform rain (contour 2)

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4. INTRODUCING THE AVERAGE REFLECTIVITY BELLOW THE BRIGHT BAND HEIGHT AS A DISCRIMINATORY VARIABLE

In case of having low convection inside stratiform rain it is tried to distinguish between them by computing the average reflectivity below the bright band for each observed VPR, $\overline{Z}_{bbb}$, (Figure 9). Convective VPRs show high values of reflectivity from the ground to the heights next to the ecotop (Figure 9). In case of Stratiform VPRs the reflectivity remains constant with height (at values lower than the values of convection for the same heights) until the bright band, where they show an increasing peak of reflectivity. So, it is expected that $\overline{Z}_{bbb}$ is lower in case of stratiform rain as is showed in Figure 9 and Figure 10.

In Figure 11 is showed how $\overline{Z}_{bbb}$ discriminates correctly between stratiform rain and low convection in case of radar image of Figure 8.

However this variable is sometimes not able to discriminate successfully between low convection and stratiform rain (Figure 12).

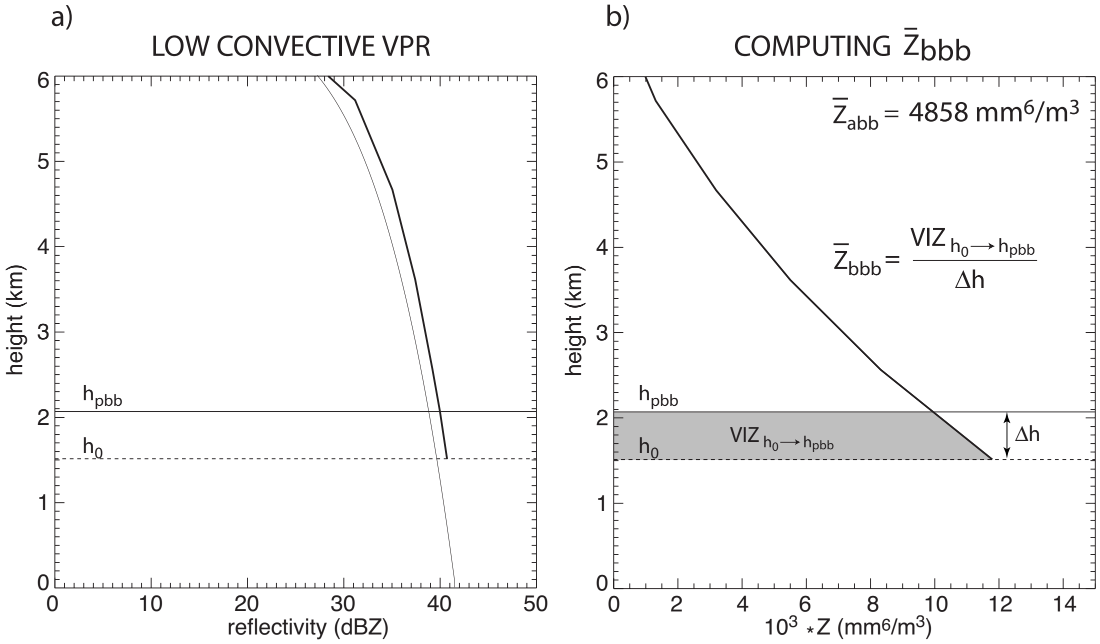

Fig 9. This figure illustrates how $\overline{Z}_{bbb}$ is obtained for a low convective VPR. In a) the observed profile (strong line) that our radar would observe over an original low convective profile (weak line) is presented. In b) the vertical profile of Z in mm^6/m^3 is showed. The grey area corresponds to the Vertical Integrated Z (VIZ) from the height of the lowest observation to the bright band. $\overline{Z}_{bbb}$ is computed dividing this area by the integrating height interval.

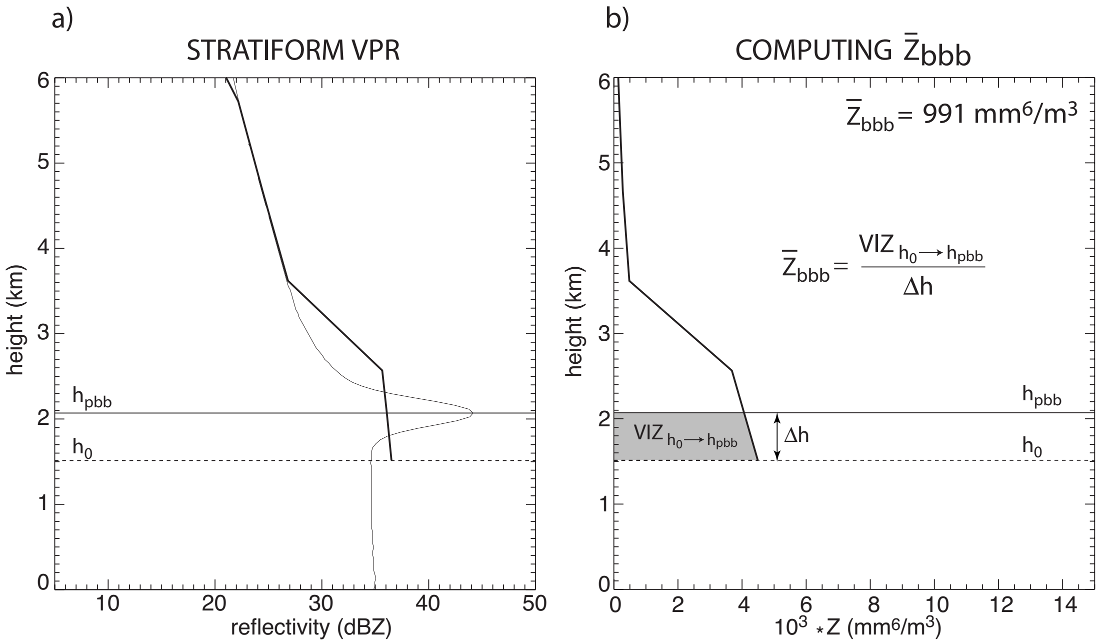

Fig 10. This figure illustrates how $\overline{Z}_{bbb}$ is obtained for a stratiform VPR. In a) the observed profile (strong line) that our radar would observe over an original stratiform profile (weak line) is presented. In b) the vertical profile of Z in mm^6/m^3 is showed. The grey area corresponds to the Vertical Integrated Z (VIZ) from the lowest observation to the bright band. $\overline{Z}_{bbb}$ is computed dividing this area by the integrating height interval.

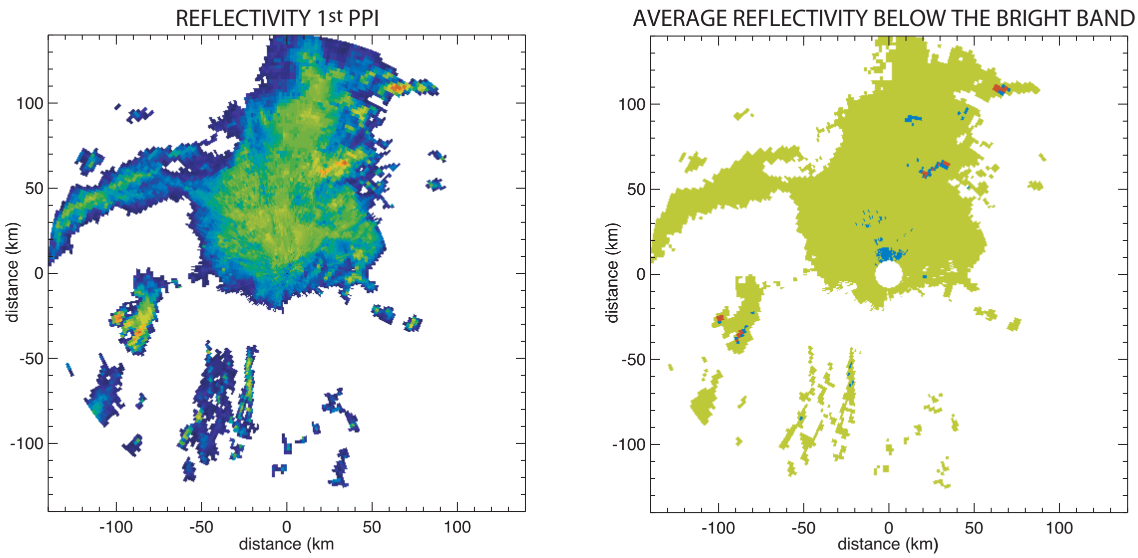

Fig 11. Representation of the average reflectivity below the bright band, $\overline{Z}_{bbb}$, for the same radar image showed in Figure 8. The yellow colour indicates low $\overline{Z}_{bbb}$ (less than the percentile 95% of the distribution of $\overline{Z}_{bbb}$ in pixels identified as stratiform by the peak criterion of the BBIA). The blue colour indicates medium $\overline{Z}_{bbb}$ (between the percentiles 95% and percentile 99% + 1000 dBZ). The red colour indicates high $\overline{Z}_{bbb}$ (greater than or equal to p99% + 1000 dBZ). In this case $\overline{Z}_{bbb}$ is able to discriminate between all types of convection (high values of $\overline{Z}_{bbb}$, in red colour) and stratiform rain (medium and low values of $\overline{Z}_{bbb}$, in blue and yellow colours).

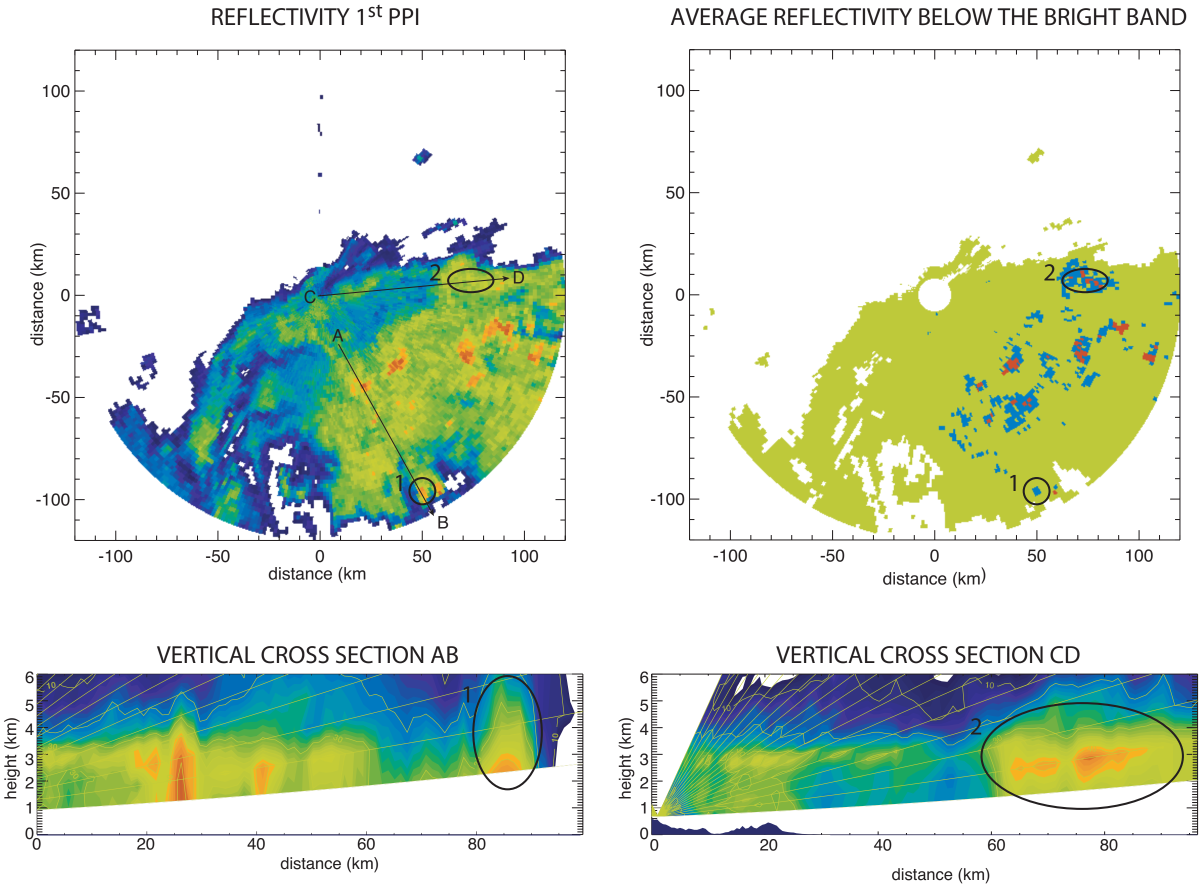

Fig 12. Representation of the average reflectivity above the bright band, $\overline{Z}_{bbb}$, for one radar image. The way to represent $\overline{Z}_{bbb}$ is the same than in Figure 11. In this case $\overline{Z}_{Bbb}$ is not able to discriminate between low convection (contour 1) and some stratiform rain (contour 2).

5. INTRODUCING THE 30 DBZ ECOTOP ALTITUDE AS A DISCRIMINATORY VARIABLE

For each VPR the 30 dBZ ecotop altitude, $h_{top,\,30\,dBZ}$, is the maximum height below which values of reflectivity less than or equal to 30 dBZ are showed. It is supposed to be useful because stratiform rain shows this value of reflectivity at the bright band maximum or, as much, 1km above the bright band. On the contrary, in case of low convection, although the maximum height for the strongest values of reflectivity (>40 dBZ) would be the same than the height of the stratiform bright band, values of reflectivity greater than 30 dBZ are showed at heights higher than 1km above.

In Figure 13 is showed how $h_{top,\,30\,dBZ}$ works discriminating stratiform and low convection in case of the radar image showed in Figure 12.

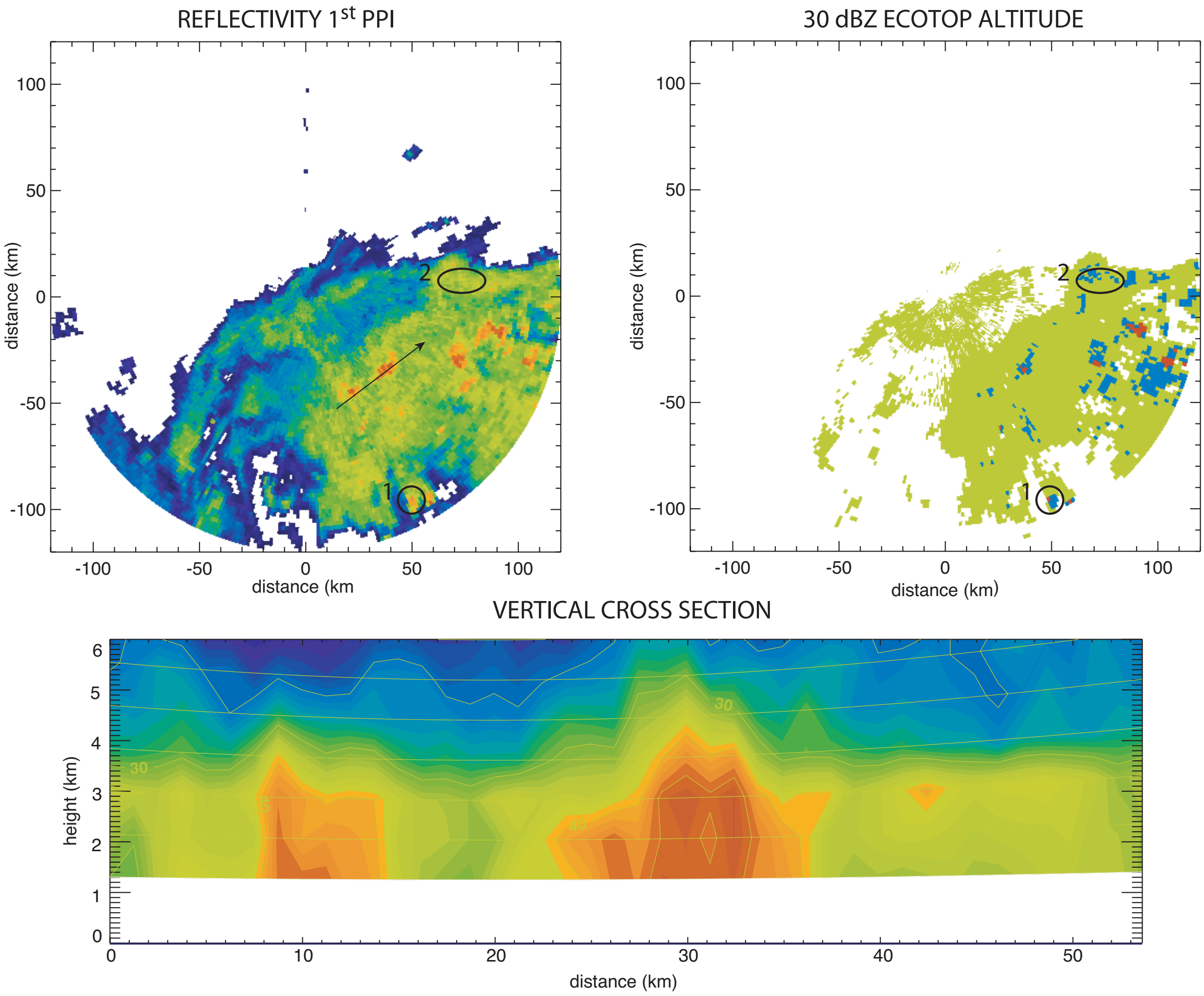

Fig 13. Representation of the 30 dBZ ecotop altitude, $h_{top,\,30\,dBZ}$, for the same radar image showed in Figure 12. The yellow colour indicates low $h_{top,\,30\,dBZ}$ (less than the percentile 95% of the distribution of $h_{top,\,30\,dBZ}$ in pixels identified as stratiform by the peak criterion of the IBBA). The blue colour indicates medium $h_{top,\,30\,dBZ}$ (between the percentile 95% and 5 km). The red colour indicates high $h_{top,\,30\,dBZ}$ (greater than or equal to 5 km). In this case $h_{top,\,30\,dBZ}$ is able to correctly discriminate between the low convection inside circle 1 (high values of $h_{top,\,30\,dBZ}$, in red colour) and stratiform rain inside circle 2 (medium and low values of $h_{top,\,30\,dBZ}$, in blue and yellow colours). However the first low convective cell of the vertical cross section shows a medium value of $h_{top,\,30\,dBZ}$ and it is not discriminated from some stratiform rain (for example rain inside circle 2).

6. AN ALGORITHM INTEGRATING THE IDENTIFYING PROCEDURES AND THE NEW DISCRIMINATORY VARIABLES

As showed in paragraphs before, neither the identifying algorithms nor the introduced discriminatory variables related to the vertical development of the precipitation are able to distinguish by themselves between convective and stratiform rain. Therefore an algorithm combining the results of applying all these criteria is proposed. This algorithm has been designed as a logical decision tree, and it works as explained in the following paragraphs.

First of all, the zone where is possible to apply the BBIA (*near zone*) and the further zone (*far zone*) where this is not possible because the first elevation is placed above the height of the bright band plus 1km, are considered separately.

Second, for each radar image, three range intervals are considered for each discriminatory variable (low values, medium values and high values) in function of their distributions of values in the pixels that are the identified as stratiform by the peak criterion of the BBIA. In particular:

- A value of $\overline{Z}_{abb}$ is considered low when is less than the percentile 99%, medium when is between the percentile 99% and 3000 mm^6/mm^3, and high when is. greater than or equal to 3000 mm^6/mm^3.
- A value of $\overline{Z}_{bbb}$ is considered low when is less than the percentile 95%, medium when is between P95% and P99% + 1000 mm^6/mm^3, and high when is greater than or equal to P99% + 1000 mm^6/mm^3.
- A value of $h_{top,\,30\,dBZ}$ is considered low when is less than the percentile 95%, medium when is between the percentile 95% and 5 km, and high when is greater than or equal to 5 km.

6.1 Classification in the near zone

In case of the *near zone* all the pixels that are identified as stratiform by the peak criterion of the BBIA are directly classified as stratiform.

All the pixels identified as convective by the CIA and not identified as stratiform by the BBIA are classified as convective.

When a pixel is identified as convective by the CIA and is not identified as stratiform by the peak criterion of the BBIA, is classified as convective if the convective cell containing the pixel shows:

a) at least one pixel with high $\overline{Z}_{abb}$ and at least one pixel with high $h_{top,\,30\,dBZ}$

b) at least one pixel not identified as stratiform by the BBIA with medium $\overline{Z}_{abb}$ and high $\overline{Z}_{bbb}$, and also some pixels with medium $\overline{Z}_{abb}$ and medium $h_{top,\,30\,dBZ}$

c) at least one pixel not identified as stratiform by the BBIA with medium $\overline{Z}_{abb}$ and high $h_{top,\,30\,dBZ}$, and also some pixels with medium $\overline{Z}_{abb}$ and medium $\overline{Z}_{bbb}$

d) at least one pixel not identified as stratiform by the BBIA with medium $\overline{Z}_{abb}$, high $h_{top,\,30\,dBZ}$ and a value of reflectivity higher than 40 dBZ, in case that the pixel is not near enough from the radar for computing the $\overline{Z}_{bbb}$

When a pixel is identified as convective by the CIA and is identified as stratiform by the gradient criterion of the BBIA, but does not correspond to one of these four cases, the pixel is classified as stratiform.

On the contrary if a pixel is identified as convective by the CIA, is not identified as stratiform by the BBIA and does not correspond to one of the four cases described before, the pixel is classified as convective in four cases:

e) it shows high $\overline{Z}_{abb}$ and high $h_{top,\,30\,dBZ}$

f) it shows medium $\overline{Z}_{abb}$, high $\overline{Z}_{bbb}$ and medium $h_{top,\,30\,dBZ}$

g) it shows medium $\overline{Z}_{abb}$, medium $\overline{Z}_{bbb}$ and high $h_{top,\,30\,dBZ}$

h) it is not near enough from the radar for computing the $\overline{Z}_{bbb}$ and it shows medium $\overline{Z}_{abb}$ and high $h_{top,\,30\,dBZ}$

Finally the rest of the pixels are classified as transition pixels if their value of reflectivity is lower than 40 dBZ and they are classified as doubt pixels (they could be pixels with no corrected ground clutter) if this value is greater or equal to 40 dBZ.

6.2 Classification in the far zone

In the far zone the pixels not identified as convective by the CIA and showing low $\overline{Z}_{abb}$ are classified as pixels that could be either stratiform or transition pixels.

If a pixel is identified as convective and corresponds to one of the four cases a), b), c) or d) described in 6.1, the pixel is classified as convective.

If a pixel is not identified as convective by the CIA, but shows high $\overline{Z}_{abb}$, or shows medium $\overline{Z}_{abb}$ and high $h_{top,\,30\,dBZ}$, the pixel is classified as convective.

Finally is a pixel not identified as convective by the CIA shows medium $\overline{Z}_{abb}$ and no high $h_{top,\,30\,dBZ}$, the pixel is identified as a doubt pixel (it could be a pixel with stratiform rain or a pixel with low convection).

6.3 Final Classification

Besides the classes introduced before, the convective pixels are separated in convective or low convective depending if they belongs to a convective cell with at least one pixel showing high $\overline{Z}_{abb}$ or not.

Therefore the image pixels are classified in seven classes:

1. stratiform pixels of the *near zone* showing a local maximum around the estimated bright band
2. stratiform pixels of the *near zone* not showing a local maximum around the estimated bright band
3. transition pixels of the near zone
4. pixels of the *far zone* which could be either stratiform or transition pixels
5. convective pixels
6. low convective pixels
7. doubt pixels.

Pixels identified as transition pixels use to correspond to pixels with light rain or to pixels in transition zones between convection and stratiform rain.

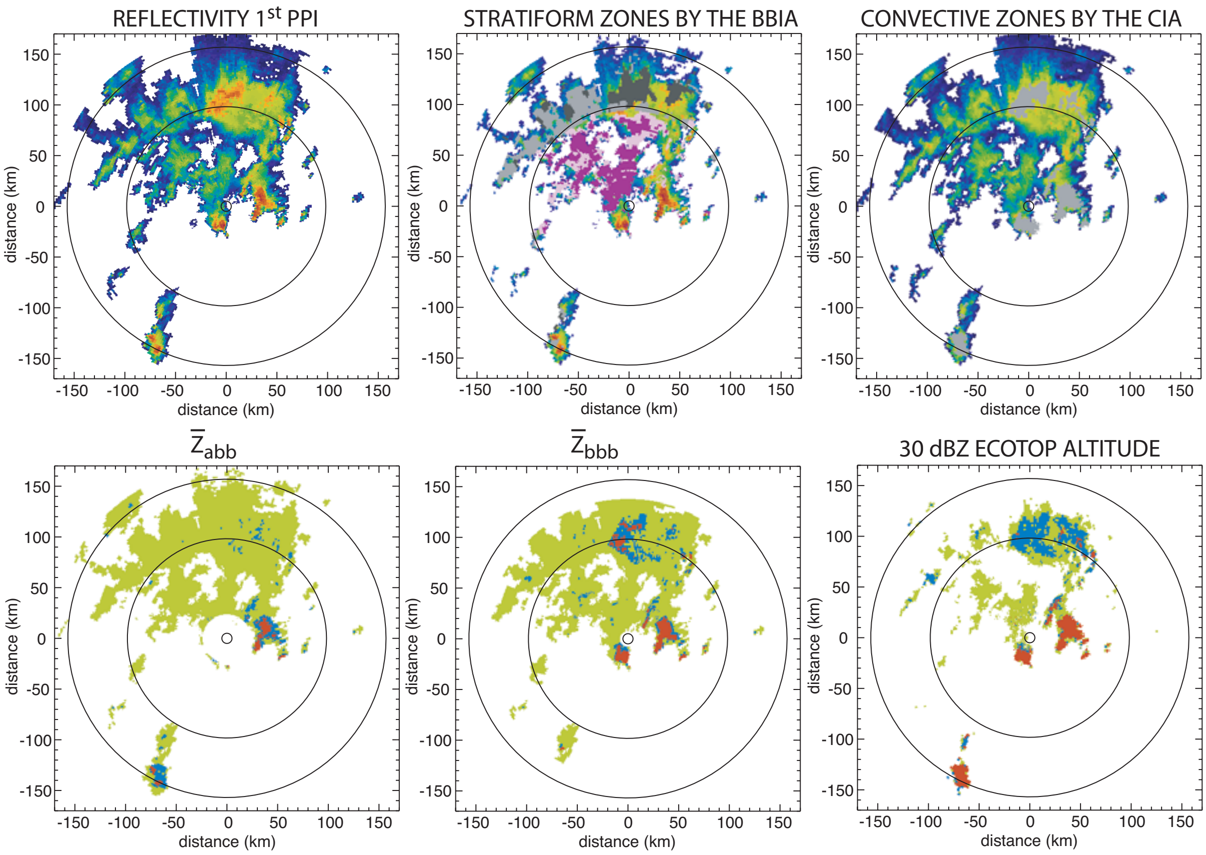

Fig. 14. Representation of the BBIA and CIA results, and the three discriminatory variables for one radar image. The way to show them is the same used in figures before.

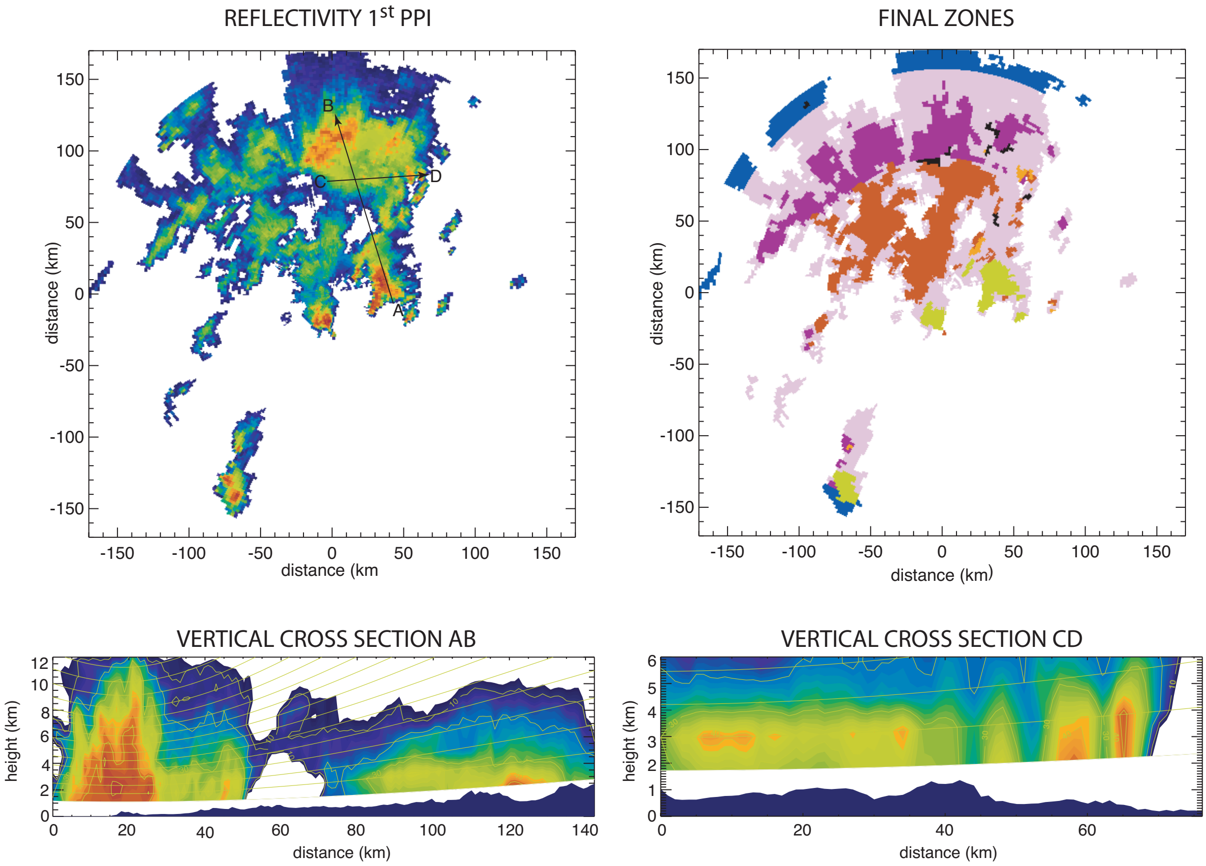

Fig. 15. Representation of the final zones resulting when the proposed classification algorithm is applied. Stratiform pixels of the *near zone* showing a local maximum around the estimated bright band are in red, stratiform pixels of the *near zone* not showing a local maximum around the estimated bright band are in dark violet, transition pixels of the near zone are in light pink, pixels of the *far zone* which could be either stratiform or transition pixels are in blue, convective pixels are in yellow, low convective pixels are in orange, and doubt pixels are in black

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An example of this kind of classification is presented in Figures 14 and 15. In this case the final algorithm correctly classifies the interception of the first PPI with the stratiform bright band as stratiform rain. All deep convective cells are clearly classified as convective. Besides most of low convective cells are also identified except three of them. Two of them are classified as doubt zones and one is wrongly identified as stratiform because its VPR shows a peak of reflectivity next to the bright band.

7. CONCLUSIONS

A new methodology for classifying convective and stratiform rain in radar images is proposed. This methodology combines the results of applying both versions of algorithms developed by Steiner et al. (1995) and Sánchez-Diezma et al. (2000) with the use of three discriminatory variables that characterize the vertical development of the precipitation. This is done applying a logical decision tree.

Before analyzing a number of representative cases from a qualitative point of view (by watching the vertical cross sections of the radar images) could be concluded that proposed methodology solves the limitations of the previous identification algorithms most of the times. However an exhaustive quantitative analysis is required.

Besides, future work is planned relative to apply fuzzy logic techniques using the results of the identification algorithms and the discriminatory variables introduced in this study.

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