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Comparison between multiparameter radar rainfall estimates and rain gauge measurements during convective storms over the Po valley(*)

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Summary. — In this paper radar rainfall estimates obtained from C-band Doppler polarimetric weather radar GPM 500C are compared with rain gauge measurements collected by three rain gauge networks during a two months period from September 1 to October 30, 1996 when many convective thunderstorms developed over the Po valley area. In order to verify the capability and the accuracy of radar rainfall estimates two different techniques of comparison with the rain gauges have been analyzed: the first one is based on pointwise comparison of conventional and/or multiparameter radar estimates with the rain gauges measurements, the second utilizes the matching of the cumulative distribution function observed by the two sensors. The results are discussed considering two different areas, where the rain gauges are at a distance less than 40 km and at a distance ranging between 40 and 80 km, respectively.

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1. – Introduction

One of the most important tasks in hydrological applications is focused on giving flood warnings with a suitable lead time in such a way that operational decisions can

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consequently be taken. The spatial information on rainfall over a large area is invaluable for the recognition of storm development and the consequent production of rainfall forecasts which can be used as essential inputs into hydrological models. The conventional approach to the estimation of surface precipitation is based on measurements of rain gauges. However, these sensors give a quantitative and accurate measurement at single locations where they are situated; in order to obtain a real rainfall measurements interpolation techniques are needed. Because of spatial variability of precipitation large errors arise; in order to reduce them a very large number of rain gauges should be provided and thereby the costs of acquisition, maintenance and management increase more and more.

An alternative approach is based on the utilization of weather radar which gives the rainfall rate estimation over large areas with very high space-time resolution. However, in spite of their wide potentiality, the main problem about radar rainfall estimates is the limited precision and accuracy, due to a variety of factors, including wrong radar calibration, ground clutter, beam blocking [1], signal attenuation and anomalous propagation [2].

In order to verify the capability and the accuracy of radar rainfall estimates two different techniques of comparison with rain gauges measurements have been proposed: the first is based on pointwise comparison of conventional and/or multiparameter radar estimates with the rain gauge measurements, the second utilizes the matching of the cumulative distribution function observed by the two sensors.

In this frame a cooperative research project between the Servizio Meteorologico Regionale of ARPA-Emilia Romagna and Radar Meteorology Group of Atmospheric Physics Institute (IFA) of the National Research Council (CNR) has been developed with the aim of comparing radar rainfall estimate and rain gauge measurements. This study is the first step to the development of a more sophisticate technique to estimate areal rainfall by radar with the aim to hydrological forecasts over river basins.

2. – Data source and instrumentation

In order to evaluate the accuracy of radar rainfall estimates meteorological events—that occurred during a two months period from September 1 to October 30, 1996—are chosen. This period is interesting from a meteorological view point because many convective thunderstorms developed over the Po valley area and one of them produced an overflow of the Reno river, which is within the area monitored by the radar. The instrumentation for rainfall measurements consists of the GPM 500C multiparameter radar and of two networks of rain gauges operated by Servizio Idrografico e Mareografico Nazionale (SIMN) and Aereonautica Militare-Ufficio Generale per la Meteorologia (UGM-AM), respectively. A sketch of the observational network used is shown in fig. 1.

2·1. *Radar data set.* – The radar data presented in this paper are collected by the Doppler dual polarized C-band GPM 500C radar. The radar is located at S. Pietro Capofiume (20 km NNE of Bologna) and is operated by SMR. The following radar observables are recorded: a) horizontal reflectivity factor (Z_{H}), b) differential reflectivity between the two linear polarizations (Z_{DR}), c) Doppler velocity (v) and the spread of Doppler spectrum (σv). These radar parameters were obtained by averaging 64 sample pairs with a pulse repetition period of 0.85 ms, the -3 dB antenna width is 0.9° and the range resolution is 250 m. With this operative mode volumetric scans composed by 10 PPI (Plan Position Indicator) at fixed antenna elevations are performed every 15 minutes on average. For this study we use only the data coming from the first elevation, *i.e.* 0.5°

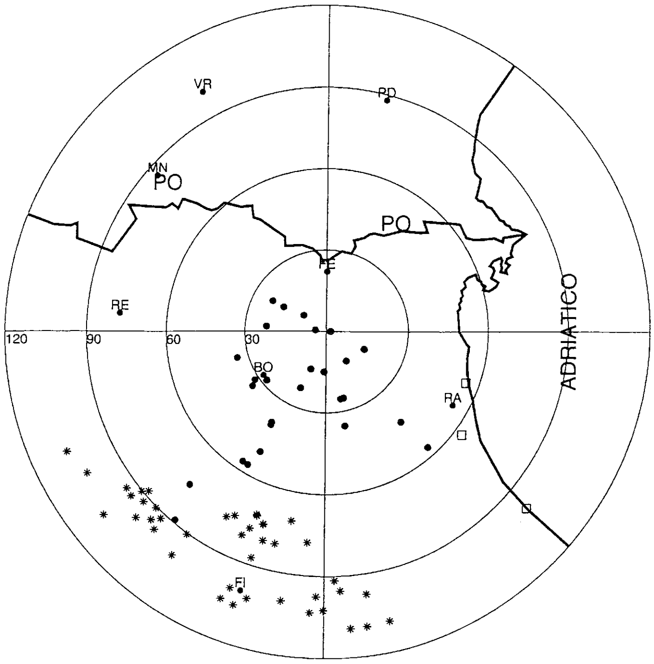

Fig. 1. – Location of the rain gauges with respect to the radar site. The rain gauge network, operated by the Servizio Idrografico e Mareografico, refers to Bologna and Pisa areas and are indicated by • and ∗; the rain gauge network operated by the Aeronautica Militare is indicated by □.

elevation.

2˙2. *Rain gauge data set*. – The rain gauge data set are collected by two different networks: the first operated by the SIMN and the second by the UGM-AM. The SIMN network, which refers to Bologna and Pisa areas, consists of 73 tipping-bucket rain gauges with an acquisition time of 30 minutes and a resolution of 0.2 mm. The UGM-AM network consists of 3 chart rain gauges from which rainfall rate can be deduced with resolution of 5 to 15 minutes, depending on the intensity. Figure 1 shows the location of rain gauges with respect to radar site. The rain gauges are distributed primarily through South-West area. The rain gauges, at a distance less than approximately 60 km, are located on the plain, whereas the others are located in the hilly region.

3. – Radar rainfall estimate

The distribution of raindrop size and shape forms the building block for obtaining the properties of the rain medium such as the reflectivity factor Z, rainfall rate R and the differential reflectivity Z_{DR}. The gamma distribution model can adequately describe the natural variations in the raindrop size distribution (RSD). This model is given by Ulbrich [3]:

$$N(D) = N_0 D^{\mu} e^{-\Lambda D}\,(\mathrm{m}^{-3}\mathrm{mm}^{-1}), \tag{1}$$

where $N(D)$ is the number of the raindrops per unit volume per unit size interval (D to $D+\Delta D$), and N_0, Λ, and μ are parameters of the Gamma distribution. Reflectivity factor at horizontal (H) and vertical (V) polarization can be expressed in terms of RSD as follows:

$$Z_{\mathrm{H,V}} = \frac{\lambda^4}{\pi^5 |K|^2} \int_0^\infty \sigma_{\mathrm{H,V}}(D) N(D)\,\mathrm{d}D\,(\mathrm{mm}^6\mathrm{m}^{-3}), \tag{2}$$

where $\sigma_{\mathrm{H,V}}$ represent the radar cross-sections at horizontal and vertical polarization, λ the wavelength and K is related to dielectric constant of water. The differential reflectivity can be expressed as [4]

$$Z_{\mathrm{DR}} = 10 \log \frac{Z_{\mathrm{H}}}{Z_{\mathrm{V}}}. \tag{3}$$

The rainfall rate R is related to RSD by

$$R = 0.6\pi \times 10^{-3} \int_0^\infty D^3 \nu(D) N(D)\,\mathrm{d}D\,(\mathrm{mm\ h}^{-1}), \tag{4}$$

where $\nu(D)$ is the terminal fall speed in still air which can be given [5] as

$$\nu(D) = 3.86 D^{0.67}\ (\mathrm{m\ s}^{-1}). \tag{5}$$

Utilizing the radar observables Z_{H} and Z_{DR}, two estimates of rainfall rate R can be obtained as follows:

$$R_{\mathrm{ZH}} = C_{\mathrm{ZH}} Z_{\mathrm{H}}^{\nu}, \tag{6a}$$

$$R_{\mathrm{DR}} = C_{\mathrm{DR}} Z_{\mathrm{H}}^{\alpha} 10^{-\beta Z_{\mathrm{DR}}}, \tag{6b}$$

where C_{ZH}, C_{DR}, ν, α and β are constants dependent on the wavelength and microphysical characteristics of precipitation. By means of a nonlinear regression analysis Gorgucci *et al.* [6] obtained the following relations at C-band:

$$R_{\mathrm{ZH}} = 2.71 \times 10^{-2} Z_{\mathrm{H}}^{0.71}, \tag{7a}$$

$$R_{\mathrm{DR}} = 7.6 \times 10^{-3} Z_{\mathrm{H}}^{0.93} 10^{-0.281 Z_{\mathrm{DR}}}. \tag{7b}$$

4. – Processing of radar data

Several preprocessing and data reduction procedures were applied to the radar data in order to compare with rain gauge measurements. The radar data was thresholded at 10 dBZ to avoid possible noise contamination whereas potential ground clutter contamination was removed by eliminating data points with near zero velocity and spectrum width.

4·1. *Radar calibration using rain gauge measurements.* – The calibration of reflectivity factor measurements has been obtained comparing radar rainfall rate estimates with the corresponding measurements of rain gauges located near the radar in order to reduce the effect due to signal attenuation. For this purpose four rain gauges are chosen: Malalbergo at a distance of 10 km from the radar, Budrio, Massarolo Bassarone at a distance of 15 km approximately from the radar; for each gauge the amount G (mm) of precipitation cumulated during the entire observation time is computed. To reduce the error due to signal fluctuations the radar rainfall estimates (7a) and (7b) were averaged over 2×2 km surface with the gauge located at the center and then for each gauge the corresponding radar rainfall accumulation R (mm) is estimated.

The ratio between the mean value of G and the mean value of R computed over the four rain gauges is 2.5; taking account of (7a) that value of ratio corresponds to a bias on the reflectivity measurement of about 5.5 dB.

4·2. *Attenuation correction procedure.* – Reflectivity measurements at C-band wavelength are affected by the attenuation of radar signal passing through precipitation that exists between the radar and the measurement cell. Differential reflectivity measurements at C-band are similarly affected by the differential attenuation between the horizontal and vertical polarization due to the propagation through the same precipitation path. The absolute specific attenuation $A_{\mathrm{H,V}}$ and specific differential attenuation A_{D} between the two polarizations are related to the RSD as follows:

$$A_{\mathrm{H,V}} = 4.343 \times 10^{-3} \Im \int_0^\infty f_{\mathrm{H,V}} N(D)\, \mathrm{d}D \;(\mathrm{dB/km}), \tag{8a}$$

$$A_{\mathrm{D}} = A_{\mathrm{H}} - A_{\mathrm{V}} \;(\mathrm{dB/km}), \tag{8b}$$

where $f_{\mathrm{H,V}}$ are the forward scattering amplitudes at H and V polarization states and $\Im$ refers to the imaginary part of a complex number. Using a nonlinear regression analysis A_{H} and A_{D} can be estimated by means of radar observables Z_{H} and Z_{DR} [7, 8].

$$A^*_{\mathrm{H}} = 6.31 \times 10^{-6} Z_{\mathrm{H}}^{0.97} 10^{-0.104 Z_{\mathrm{DR}}}, \tag{9a}$$

$$A^*_{\mathrm{D}} = 5.86 \times 10^{-7} Z_{\mathrm{H}}^{1.02} 10^{-0.030 Z_{\mathrm{DR}}}. \tag{9b}$$

Attenuation and differential attenuation cumulatively increase with the range. Therefore echoes from cells near radar are not attenuated as much as the echoes from storm cells farther from the radar. It can be assumed that the closest echo is not attenuated and the attenuation cumulatively adds up from that point. Following a cumulative correction scheme [7], the corrected value of horizontal reflectivity on dB scale and differential reflectivity at n-th range gate can be estimated as

$$\left(Z_{\mathrm{H}}\right)_n = \left(Z_{\mathrm{H}}^{\mathrm{meas}}\right)_n + 2 \sum_{i=1}^{n-1} \left(A^*_{\mathrm{H}}\right)_i \Delta r, \tag{10a}$$

$$\left(Z_{\mathrm{DR}}\right)_n = \left(Z_{\mathrm{DR}}^{\mathrm{meas}}\right)_n + 2 \sum_{i=1}^{n-1} \left(A^*_{\mathrm{D}}\right)_i \Delta r, \tag{10b}$$

where $(Z_{\mathrm{H}}^{\mathrm{meas}})_n$ and $(Z_{\mathrm{DR}}^{\mathrm{meas}})_n$ are the measured radar observables at n-th range bin, $(A^*_{\mathrm{H}})_i$ and $(A^*_{\mathrm{D}})_i$ are the estimates (9a) and (9b) of A_{H} and A_{D} at i-th range bin, respectively; Δr is the range spacing and the summation refers to the measurement cells up to $n-1$ range bins. By simulation it was found that at C-band for rainfall less than 300 mm/h the values of specific and differential attenuation are less than 0.75 dB/km and 0.25 dB/km, respectively. The correction procedure is performed in such a way that, when in a measurement cell A_{H} and A_{D} are greater than those values, the attenuation values are referred to those of preceding radar cell. It can be pointed out that in the presence of calibration error in reflectivity factor can drastically deteriorate the estimates corrected for attenuation.

5. – Data analysis and results

In order to compare correctly the two data sets, we have to take account of the fact that the rain gauge measurement gives an accumulated value of the rainfall rate over the integration time, whereas the radar provides an instantaneous measurement. For this purpose the radar data were first linearly interpolated to obtain the time function of the rainfall rate and then radar estimates were obtained integrating the rainfall rate over each time of rain gauge. To quantitatively describe the performance of the radar algorithms to estimate rainfall we have considered the following figures of merit:

i) bias (G/R) defined as the ratio between the precipitation amount of rain gauge and the corresponding cumulated precipitation estimated by radar;

ii) fractional Standard Error (FSE) defined as

$$FSE = \frac{\left[\frac{1}{N}\sum_{i=1}^{N}(G_i - R_i)^2\right]^{1/2}}{\frac{1}{N}\sum_{i=1}^{N} G_i}, \tag{11}$$

where N represents the number of observations for each rain gauge;

iii) standard error of normalized bias defined as

$$BSD = \left[\frac{1}{N}\sum_{i=1}^{N}\left(\frac{G_i - R_i}{G_i}\right)^2\right]^{1/2}; \tag{12}$$

iv) correlation coefficient between radar and rain gauge measurements defined as

$$\rho = \frac{\frac{1}{N}\sum_{i=1}^{N}\left(G_i R_i\right) - \overline{GR}}{\sigma(G)\sigma(R)}, \tag{13}$$

where $\bar{G}$ and $\bar{R}$ represent the mean values of radar and rain gauge estimates during the entire observation time, $\sigma(G)$ and $\sigma(R)$ are the respective standard deviations;

v) slope (S) of the scatter between gauge and radar measurements

$$S = \frac{\sum_{i=1}^{N} R_i G_i}{\sum_{i=1}^{N} G_i^2}. \tag{14}$$

TABLE I. – *Parameters shown for each range gauge (ID): 1) distance (D) from the radar, 2) the amount of precipitation cumulated (G), 3) the amount of precipitation (R) estimated by radar, 4) the Fractional Standard Error (FSE), 5) the standard error of the normalized bias (BSD), 6) the bias (G/R) and 7) the correlation coefficient ρ between radar and rain gauge measurements.*

ID	*D*	*G*	*R*	*FSE*	*BSD*	*G/R*	ρ
31	4.1	183.6	79.7	1.4	1.4	2.3	0.74
30	10.2	218.4	61.8	1.7	0.1	3.5	0.53
25	14.9	211.6	74.6	1.2	1.2	2.8	0.57
26	14.9	226.8	107.4	1.5	0.1	2.1	0.52
29	15.2	214.2	83.1	1.2	1.0	2.5	0.45
28	18.1	163.6	64.2	1.2	1.2	2.5	0.67
32	25.4	207.2	81.4	1.4	1.2	2.5	0.45
35	28.2	181.8	62.8	1.1	0.7	2.9	0.72
36	33.7	228.6	70.6	1.2	0.7	3.2	0.66
27	34.3	164.9	51.8	1.4	0.9	3.2	0.55
24	39.8	227.2	79.1	1.4	1.8	2.9	0.31
33	43.0	293.8	69.3	1.8	2.1	4.2	0.45
34	56.7	156	62.9	1.1	1.0	2.5	0.60
8	70.7	213.2	76.0	1.2	0.8	2.8	0.59
9	74.3	176.8	68.7	1.3	0.7	2.6	0.60
12	75.4	168.4	71.1	1.2	0.8	2.4	0.60
10	77.8	176.6	84.4	1.1	0.7	2.09	0.49
14	77.2	169.8	70.3	1.2	0.9	2.4	0.49
6	80.8	173.2	68.5	1.3	0.8	2.5	0.40
7	80.1	156.2	77.2	1.1	0.7	2.0	0.53
19	90.3	266.6	55.1	1.3	0.9	4.8	0.45
21	90.5	190.2	63.9	1.6	1.3	2.1	0.32
1	91.6	220	70.8	1.4	1.2	3.1	0.54
20	94.5	243	44.4	1.4	0.8	5.5	0.54
22	94.9	195.6	45.8	1.6	0.9	4.3	0.34
2	95.4	206.4	47.1	1.6	0.8	4.4	0.58
3	97.5	297.8	78.5	1.5	1.2	3.8	0.55
11	97.5	267.6	60.1	1.6	0.8	4.4	0.57
23	98.3	187.8	37.2	1.5	0.8	5.0	0.41
13	99.9	142	27.8	1.8	0.8	5.1	0.41
15	100.4	169.6	37.3	1.5	0.9	4.5	0.38
5	103.4	378.8	50.6	2.3	0.9	7.5	0.19
16	105.8	165.4	26.4	1.7	1.0	6.3	0.27
17	106.5	176	27.9	1.2	0.9	6.3	0.58
18	106.8	123	17.5	1.4	0.9	7.0	0.39
4	109.3	196	31.3	1.5	1.0	6.3	0.45

In table I the following parameters are shown for each rain gauge (ID): 1) the distance (D) from the radar, 2) the amount of precipitation cumulated (G), 3) the amount of precipitation (R) estimated by radar, 4) the Fractional Standard Error (FSE), 5) standard error of the normalized bias (BSD), 6) the bias (G/R) and 7) the correlation coefficient ρ between radar and rain gauge measurements. It can be pointed out that the radar always underestimates the gauge measurements, although the amounts of precipitation measured by close gauges are comparable; moreover, the more is the distance

TABLE II. – *Parameters shown for each range gauge (ID): 1) distance (D) from the radar, 2) the amount of precipitation cumulated (G), 3) the amount of precipitation (R) estimated by radar, 4) the Fractional Standard Error (FSE), 5) the standard error of the normalized bias (BSD), 6) the bias (G/R) and 7) the correlation coefficient* ρ *between radar and rain gauge measurements when the correction bias of 5.5 dB is applied on the reflectivity measurements.*

ID	*D*	*G*	*R*	*FSE*	*BSD*	*G/R*	ρ
31	4.1	183.6	195.8	1.2	3.3	0.9	0.74
30	10.2	218.4	151.9	1.5	2.0	1.4	0.53
25	14.9	211.6	183.3	1.2	2.6	1.1	0.57
26	14.9	226.8	263.9	2.5	2.0	0.9	0.52
29	15.2	214.2	206.4	1.4	2.3	1.0	0.45
28	18.1	163.6	157.7	1.4	2.8	1.0	0.67
32	25.4	207.2	200.1	2.1	2.8	1.0	0.45
35	28.2	181.8	154.3	0.9	0.7	1.2	0.72
36	33.7	228.6	173.6	1.0	0.7	1.3	0.66
27	34.3	164.9	127.3	1.3	1.8	1.3	0.55
24	39.8	227.2	194.5	1.7	4.3	1.2	0.31
33	43.0	293.8	170.4	1.7	5.1	1.7	0.45
34	56.7	156	154.6	1.3	2.3	1.0	0.6
8	70.7	213.2	186.9	1.3	1.2	1.1	0.59
9	74.3	176.8	168.9	1.3	1.1	1.0	0.6
12	75.4	168.4	174.6	1.3	1.8	0.1	0.6
10	77.8	176.6	207.5	1.7	1.3	0.8	0.49
14	77.2	169.8	172.9	1.4	2.0	0.1	0.49
6	80.8	173.2	168.4	1.4	1.7	1.0	0.4
7	80.1	156.2	189.6	1.5	1.4	0.8	0.53
19	90.3	266.6	135.4	1.2	1.3	1.1	0.45
21	90.5	190.2	157.0	1.7	2.1	1.2	0.32
1	91.6	220	174	1.4	2.5	1.3	0.54
20	94.5	243	109.2	1.2	0.1	2.2	0.54
22	94.9	195.6	112.6	1.5	1.7	1.7	0.34
2	95.4	206.4	115.7	1.4	0.9	1.8	0.58
3	97.5	297.8	192.9	1.4	2.7	1.5	0.55
11	97.5	267.6	147.7	1.4	1.1	1.8	0.57
23	98.3	187.8	91.4	1.4	1	2.1	0.41
13	99.9	142	68.4	1.6	0.9	2.9	0.41
15	100.4	169.6	91.6	1.3	1.6	1.8	0.38
5	103.4	378.8	124.3	2.3	1.5	3.0	0.19
16	105.8	165.4	64.8	1.5	1.8	2.5	0.27
17	106.5	176	68.5	0.1	0.9	2.6	0.58
18	106.8	123	42.1	1.3	0.9	2.9	0.39
4	109.3	196	76.9	1.4	1.8	2.5	0.45

of the gauge from the radar the greater is the underestimation. *FSE* is greater than 100% on average, meanwhile the correlation coefficient ranges between 0.7 to 0.3 and decreases with the range, as it is expected because the radar measurements decorrelate with respect to gauge measurements as range increases. In table II the same parameters as in table I are shown, where the correction bias of 5.5 dB is applied on the reflectivity factor measurements. A significant improvement in the ratio G/R can be noted; however high values of G/R are still present for the rain gauges at a distance greater than 80 km.

TABLE III. – *Parameters shown for rain gauges within the area A (0–40 km) and area B (40–80 km), respectively : 1) the Fractional Standard Error (FSE), 5) the standard error of the normalized bias (BSD), 6) the slope (S) of the scatter between radar and rain gauge measurements, when and without the bias and attenuation corrections.*

	$R < 40\,\text{km}$			$40\,\text{km} < R < 80\,\text{km}$		
	FSE	*BSD*	*S*	*FSE*	*BSD*	*S*
Without correction	0.64	0.64	2.73	0.65	0.65	2.72
With calibration correction	0.17	0.16	1.11	0.24	0.17	1.11
With attenuation	0.17	0.16	1.02	0.39	0.40	0.87
CDF method	0.12	0.11	1.04	0.32	0.24	1.35

For this reason our analysis is focused on two areas, the first (A) ranging between 0 to 40 km and the other (B) between 40 to 80 km. The results in table III show that for the rain gauges within the area A the parameters are negligibly affected by the attenuation correction ($FSE = 0.17$, $BSD = 0.16$, $S = 1.02$), as it is expected. On the other hand, for the area B the performance of the parameters is significantly deteriorated ($FSE = 0.39$, $BSD = 0.40$, $S = 0.87$); this can be due to the increasing distance from the radar and to the noisy Z_{DR} measurement which affects the estimate of attenuation along the path.

6. – Radar–rain-gauge comparison using Cumulative Distribution Function (*CDF*) of rainfall

The comparison between radar and rain gauge estimates of rainfall can be obtained from the matching of the Cumulative Distribution Function (*CDF*) of the two measurements [9]. Gorgucci *et al.*, [10] and Gorgucci *et al.*, [11] have applied this method to S-band and C-band polarimetric measurements. In our analysis we utilize the Z_{H} based algorithm described by (6a) to estimate the rainfall rates used in the computation of the *CDF*. The procedure for estimating the coefficients of radar rainfall algorithm is as follows:

1) For a given starting guess of coefficients C_{ZH} and ν evaluate the radar rainfall estimate at each rain gauge location as described in the previous section. Typically the initial guess is based on the relation (7a).

2) Construct the *CDF* based on the result of step 1).

3) Construct the *CDF* based on rain gauges observations.

4) Compute the square of the difference between radar and rain gauge estimates for a fixed value of *CDF*. The root square of the integral, over the entire range of *CDF* values, gives an index of error between the two estimates.

5) Obtain the coefficients of (6a) minimizing the error index between the two estimates.

This technique is specialized for the two different areas A and B and the resulting parameterizations are

(15a) $$R_{ZH} = 1.35 \times 10^{-1} Z_H^{0.612},$$

(15b) $$R_{ZH} = 8.4 \times 10^{-2} Z_H^{0.644}.$$

As for the parameterization (15a) the results show a good improvement in *FSE* and *BSD* merit figures of about 5% with respect to the parameterization (7a).

7. – Conclusion

A cooperative research program between the Servizio Meteorologico Regionale of ARPA-Emilia Romagna and the Radar Meteorology Group of Atmospheric Physics Institute (IFA) of the National Research Council (CNR) has been developed to compare radar rainfall estimates obtained by C-band Doppler polarimetric radar GPM 500C, and rain gauge measurements collected by three different rain gauge networks.

For this study meteorological events—that occurred during a two months period from September 1 to October 30, 1996—are chosen. That period was interesting from a meteorological view point because many convective thunderstorms developed over the Po valley area.

A preliminary quality control of radar data was performed in order to avoid any effect due to ground clutter, system noise and anomalous propagation. In order to verify the accuracy of reflectivity factor measurements a procedure based on the comparison of cumulative amount of precipitation estimated by radar and gauge was used. To reduce the effect due to the signal attenuation rain gauge very close to the radar was chosen. The results show a bias on reflectivity factor measurements of 5.5 dB.

The signal attenuation is not negligible at C-band; for this purpose a technique of attenuation correction based on the Z_H measurements was applied, because the multi-parametric procedure based on Z_H and Z_{DR} resulted too noisy. The applied correction technique shows a significant improvement on the rain estimation if the cumulative attenuation is not high, as it is well established in the literature.

In order to compare radar and rain gauge measurements two different areas were considered; the first where the rain gauges were at a distance less than 40 km, and the second one where the distance of rain gauges ranges between 40 km to 80 km. The most important result of this study is that the fractional standard error between radar and rain gauges measurements referring to the entire data set is 17% for the nearest area to the radar and 39% for the farther.

The positive results obtained in this cooperative study suggest to develop a more sophisticate technique to estimate areal rainfall by radar in order to perform hydrological forecasts over river basins.

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