Internationales Symposion
INTERPRAEVENT 2004 – RIVA / TRIENT

AN EVALUATION OF RADAR RAINFALL ESTIMATES FOR HEAVY RAINFALL EVENTS IN AN ALPINE REGION

Fabrizio Tonelli[1], Marco Borga[2], Mauro Tollardo[3] and Marta Pendesini[4]

ABSTRACT

Storms that potentially produce extreme rainfall and flooding present a special challenge for radar rainfall estimation. The authors assess the utility of weather radar in the investigation of extreme rain-producing storms through case studies of storm events. Eight storm events that produced extreme rainfalls, debris flows and floods in north-eastern Italian Alps are examined by using data from the Monte Macaion radar (located in the Trentino-Alto Adige region). The analyses illustrate the significance of vertical profile of radar reflectivity and scan elevation selection in the radar monitoring of convective rainfall events. Results are presented for interscan comparison, at hourly and sub-hourly rainfall accumulations, and for radar-raingauge intercomparisons.

Key-words: precipitation; weather radar; radar hydrology; vertical profile of radar reflectivity

INTRODUCTION

Weather radar offers an unprecedented opportunity to improve our ability of observing extreme storms and quantifying their associated precipitation (Smith et al., 1996; Krajewski and Smith, 2002; Creutin and Borga, 2003). One of the greatest advantages of radar is the capability to monitor extreme rainfall producing storms on a wide range of spatial and temporal scales. This is especially important for the analysis of convective events and thunderstorms. Equally striking is the range of issues that arise in radar-based rainfall estimation, particularly when this is required on a mountainous area, characterised by complex terrain (Wilson and Brandes, 1979; Austin, 1987; Borga et al., 2000; Dinku et al., 2002; Borga et al., 2002). In this paper we examine a number of issues that arise in measurement of rainfall for short lived, very intense storms by a C- band radar located in an alpine region (Trentino – Alto Adige region, in north-eastern Italy), with specific attention on analysis of effects due to the vertical variability of precipitation characteristics.
It is well known that errors associated with the beam elevation and the variability of precipitation with height are among the most important sources of uncertainty in a mountainous radar operation context. Specifically, to avoid contamination from ground

1 Conctact person, Department of Land and Agroforest Environments, AGRIPOLIS, University of Padova, via dell'Università, 16 , Legnaro, IT-35020 (Tel.: +39-049-8272695; Fax: +39-049-8272686; email: fabrizio.tonelli@unipd.it)
2 Department of Land and Agroforest Environments, AGRIPOLIS, University of Padova
3 Ufficio Idrografico, Provincia Autonoma di Bolzano, Italy
4 METEOTRENTINO, Provincia Autonoma di Trento, Italy

returns, and partial or total beam blocking due to the orography, radar data from relatively large elevation sweeps are used. The use of higher elevation sweeps increases the altitudes at which the radar observes the rainy atmosphere. Therefore, if either the nature or intensity of the precipitation varies with height, radar indications may not be representative of surface rainfall.
The combination of the vertical variability of reflectivity with the geometric characteristics of the radar sampling induces biases in radar rainfall estimates that are range-related. Range-related biases are not strictly specific to a mountain setting, but are enhanced by the presence of the relief and the altitude of the radar location. Most of the existing correction procedures for range-related biases are based on the identification of the mean vertical profile of reflectivity (*VPR*), and converting radar reflectivity measurements of higher altitudes to their surface level values, according to the influence of this *VPR* (e.g., Smith, 1986; Joss and Waldvogel, 1990; Joss and Pittini, 1991; Kitchen et al., 1994; Joss and Lee, 1995; Hardaker et al., 1995; Andrieu and Creutin, 1995). These issues have been analysed for mostly stratiform precipitation (Joss and Lee, 1995; Vignal et al., 1999; Borga et al., 2002). *VPR* effects play an integral role also for convective events (Baeck and Smith, 1998). However, these effects have received less attention, essentially because their correction is made difficult by the intrinsic characteristics of the convective events, i.e. higher space-time variability of *VPR* structure and relatively small extension of the precipitation field.

STUDY REGION AND DATA

The data used in this study were collected by the C-band Doppler radar located on the Monte Macaion (1860 m a.s.l.), in northern Italy, close to Bolzano (Figure 1a,b). Technical characteristics of the radar are reported in Table 1. The region covered by the radar ranges from 200 m a.s.l. on the valley bottom to 3900 m a.s.l. (corresponding to the highest mountains in north-eastern Italy).

a) b)

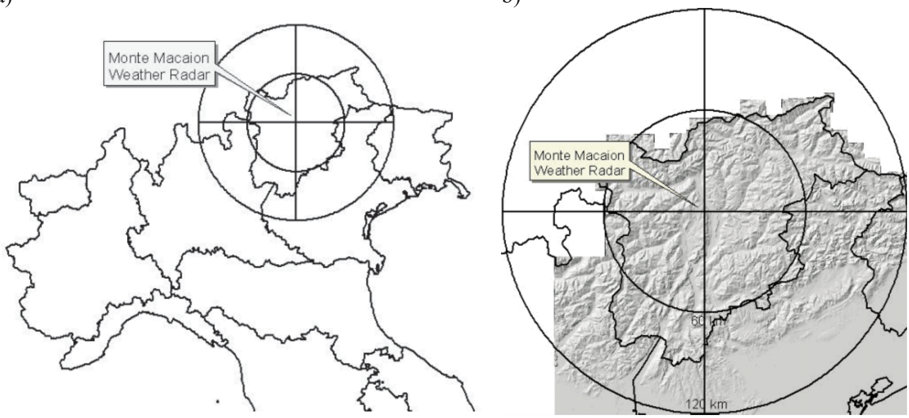

Fig. 1: a) Position of Monte Macaion Weather Radar. b) Monte Macaion Weather Radar and surrounding topography

Tab. 1: Monte Macaion Weather Radar: technical characteristics.

Parameter	*Value*
Maximum range (doppler)	120 km
Resolution in range	250 m
3 dB beamwidth	0.9°
Peak power	307.0 kW
Wavelength	5.3 cm (C band)
Update time	6 minutes
Pulse duration	0.8 µs
Gain	45.8 dB
Scan strategy (13 elevations)	1.0°; 2.0°; 3.0°; 4.0°; 5.0°; 6.0°; 8.0°; 10.0°; 13.0°; 16.0°; 19.5°; 24.0°; 45.0°

The radar site has been selected to ensure good visibility on the covered region. However, lack of visibility still remains a problem, as can be noted in Figure 2a,b, where the percentage of beam power blocked by orography at each azimuth and range is reported for two elevation scans (1.0° and 2.0° , respectively). These maps have been generated based on a 40 m DEM and an algorithm for ground clutter and occlusion simulation (Borga and Giaretta, 1992; Andrieu and Creutin, 1995). Interaction of the radar beam with the ground generates also false echoes not related to precipitation (ground clutter). These effects are more pronounced for those azimuths which are non-obstructed at close ranges - indeed clutter is often received through the sidelobes of the antenna. The radar is equipped with Doppler techniques to identify and filter out suspected ground echoes. However, it is well known that these techniques cannot ensure complete clutter elimination. Research is underway to add further sources of information to detect and eliminate clutter.

Radar and gauge data have been collected for eight storm events (Table 2), characterised by high rain rates and hail. These events caused landsliding, debris flows and flash floods in various sites of the monitored region. The name of the most hitted site is reported in Table 2 for each storm event. Note that some events in Table 2 are characterized by long duration; this means that for those cases more events, clustered in time, were considered. One should also consider that max rain rate and rainfall accumulation reported in Table 2 are those measured by raingauges; for some cases these measurements have limited representativeness, since the raingauge network captured only part of the storm event.

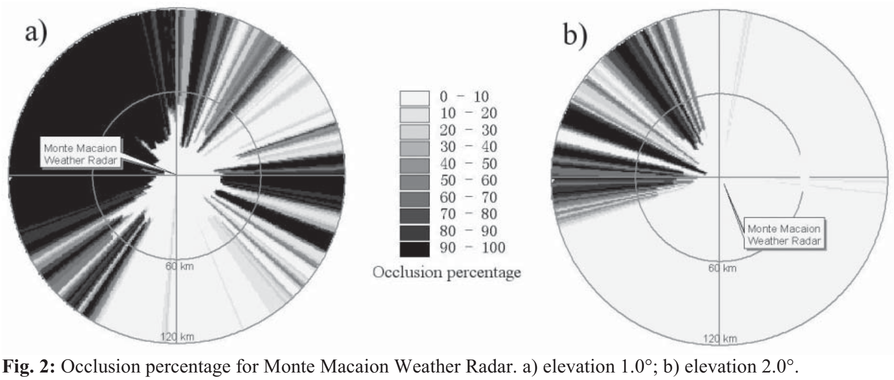

Fig. 2: Occlusion percentage for Monte Macaion Weather Radar. a) elevation 1.0°; b) elevation 2.0°.

AN ADJUSTMENT PROCEDURE FOR VERTICAL PROFILE OF REFLECTIVITY

In this study we aim to quantify the impact of *VPR*-related effects on radar rainfall estimation for heavy precipitation events, and to propose an adjustment procedure. Attenuation effects and hail contamination were not considered in this analysis, even though these problems play a non negligible role for the studied events.

Due to the radar sampling geometry, radar rainfall estimation is necessarily subject to biases that are range-related. Since the beam elevation angle is typically set to relatively high positive values to avoid beam occlusion and ground effects, the altitude of the radar sampling volume strongly depends on the radar range. Therefore, range-related errors mirror the vertical structure of the reflectivity field as it is perceived by the radar at various ranges. The vertical variability of reflectivity is due to several effects including the growth (or evaporation) of hydrometeors, vertical air motion, change of hydrometeors' phase (ice to liquid water, for example), and precipitation enhancement due to orography, among other effects (e.g., Joss and Waldvogel, 1990). For more stratiform precipitation systems, bright band enhancement is the most prominent source of range-dependent bias. The bright band is caused by the presence of a layer of enhanced reflectivity, which corresponds to the melting layer region, where snowflakes melt to form raindrops. This rainfall overestimation occurs mainly at close and intermediate ranges (10 to 60 km), where most radars can resolve the melting layer structure. At further ranges bright band compensates for the reduced reflectivity aloft and at even longer ranges underestimation due to cloud overshooting occurs. This study focuses on range-dependent biases that arise at mid-ranges (40-90 km) due to the requirement of using relatively high elevation (2.0° and 3.0°) radar scans to avoid ground effects and beam occlusion close to the radar site. At these elevations and ranges rainfall is detected but its surface value can be heavily underestimated.

The adjustment procedure used, developed by Vignal et al. (1999), solves the inverse problem of retrieving the vertical reflectivity profile from radar measurements using discrete inverse theory. The basic assumption of the method is that *VPR* is homogeneous over the observed area. It requires reflectivity measurements from at least two elevation scans, and is based on the calculation of reflectivity ratios measured at the different elevation angles over the same location. The method requires also an initial estimate of the *VPR* ('a priori *VPR*'). Identification of *VPR* allows computation of a correction function, which depends on the *VPR* and the radar beam geometry. The correction function is applied to the precipitation fields from a given elevation scan to retrieve the surface reflectivity field.

Mainly convective events, as those analysed here, cover a limited extension in range, even though the convective cores are embedded in stratiform rain. It is therefore extremely difficult to use instantaneous or even storm-averaged data to retrieve the *VPR* structure, since data may be missing to identify the full structure of the *VPR*, required to extrapolate radar echoes to the ground. Due to this reason, we used a mean *VPR* computed over all the studied events. The mean *VPR* was computed on the basis of the lower five elevations (using sectors likely free from beam occlusion and ground clutter), combined by using a simple accumulation of the azimuthal averages. An uncertainty associated with using mean *VPR* estimates for this correction is its spatial variability (Borga et al., 1997).

Rainfall accumulation over pre-defined time steps were obtained by averaging images belonging to the considered time interval; a general *Z-R* relationship was used to convert reflectivity Z to rain-rate R ($Z=aR^b$, with a=300 and b=1.4).

The identified *VPR* is shown in Figure 3. The *VPR* structure shows a well defined peak at 1.2 km above the radar and a roughly exponential decrease at higher altitudes. The structure is more typical of stratiform rain rather than of convective precipitation. This is not unexpected, since the studied events represented both cases of convection embedded in stratiform rain and unorganized convection with stratiform rain. Attempts to use existing schemes for convective/stratiform echo classification (Steiner et al., 1995; Biggerstaff and Listemaa, 2000), helping to identify in this way specific *VPR* structures for stratiform and for convective environments, proved unsuccessful on the analysed events.

Tab. 2: Events analysed.

N.	*Location*	*Starting time (UTC) and duration (hours)*	*Number of gauges*	*Max cumulated rainfall (from raingauges) (mm)*	*Max rain rate (from raingauges) (mm hr^{-1})*
1	Val Pusteria-Vandoies	12/7/02 17.00; 7	16	51.6 (Selva dei Molini)	35.0 (Selva dei Molini)
2	Val Passiria	5/8/02 20.00; 3	4	24.6 (S. Leonardo in Passiria)	17.0 (S Leonardo Pass.)
3	Sciliar	25/5/03 14.00; 6	2	20.2 (Fiè allo Sciliar)	17.4 (Tires)
4	Merano – Rifiano	5/6/03 17.00; 38	3	15.0 (Merano Quarazze)	8.2 (Merano Quarazze)
5	Val di Non	6/6/03 19.00; 9	3	44.8 (Romeno)	26.8 (Fondo)
6	Aldino	9/6/03 6.00; 18	2	13.4 (Nova Levante)	13.4 (Nova Levante)
7	Val di Vizze	11/6/03 13.00; 3	3	8.6 (Vipiteno-Convento)	7.6 (Vipiteno – Convento)
8	Trento / Sarentino	16/6/03 21.00; 27	11	70.4 (Zambana)	35.6 (Zambana)

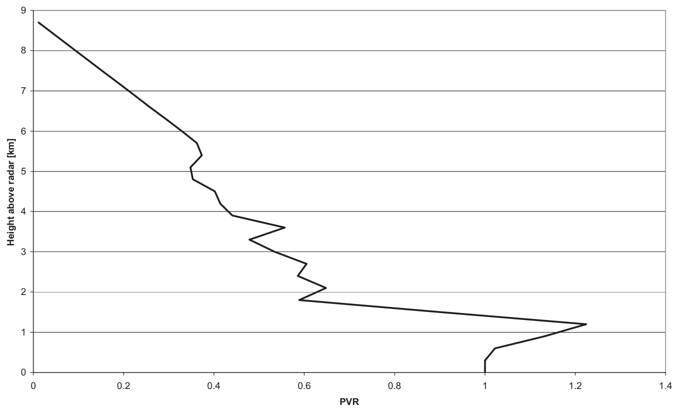

Fig. 3: Identified *VPR*.

ALGORITHM EVALUATION

Quantitative analyses of radar error sources and evaluation of the proposed adjustment procedure are performed on the basis of (1) range-dependent inter-elevation radar rainfall statistics and (2) radar-raingauge rainfall difference statistics. Two criteria have been selected for range-dependent radar rainfall statistics:

Mean Relative Error (MRE)

$$MRE = \frac{\sum_{i=1}^{N_t}(P_i - O_i)}{\sum_{i=1}^{N_t} O_i} \qquad (1)$$

Fractional Standard Error (FSE)

$$FSE = \frac{\left\{\frac{1}{N_t}\sum_{i=1}^{N_t}(P_i - O_i)^2\right\}^{0.5}}{\frac{1}{N_t}\sum_{i=1}^{N_t} O_i} \qquad (2)$$

where O_i is the reference variable for the *i*-th time step, P_i is the corresponding predicted variable, N_t is the number of time-steps considered for the evaluation.
The range-dependent inter-elevation assessment aims to evaluate the degree of inter-elevation homogeneity achieved from the *VPR*-based adjustment technique. The expectation is that the *VPR* adjustment would minimise the range dependence and inter-elevation bias seen in the unadjusted data statistics, which is an effect of the non-uniform *VPR* described earlier.

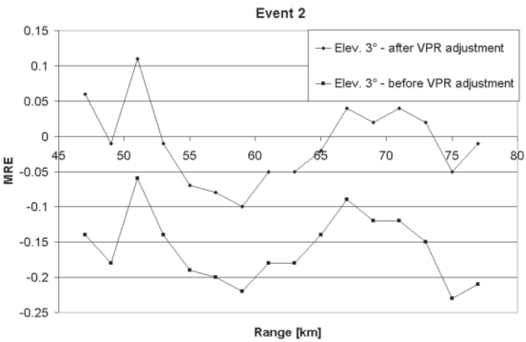

Fig. 4: Inter-elevation comparison: MRE values between elevations 2.0° and 3.0° before and after VPR adjustment (Event 2).

Demonstrating a successful elimination of the range dependence for the different elevation scans is crucial for effective radar rainfall estimation, particularly in complex terrain.

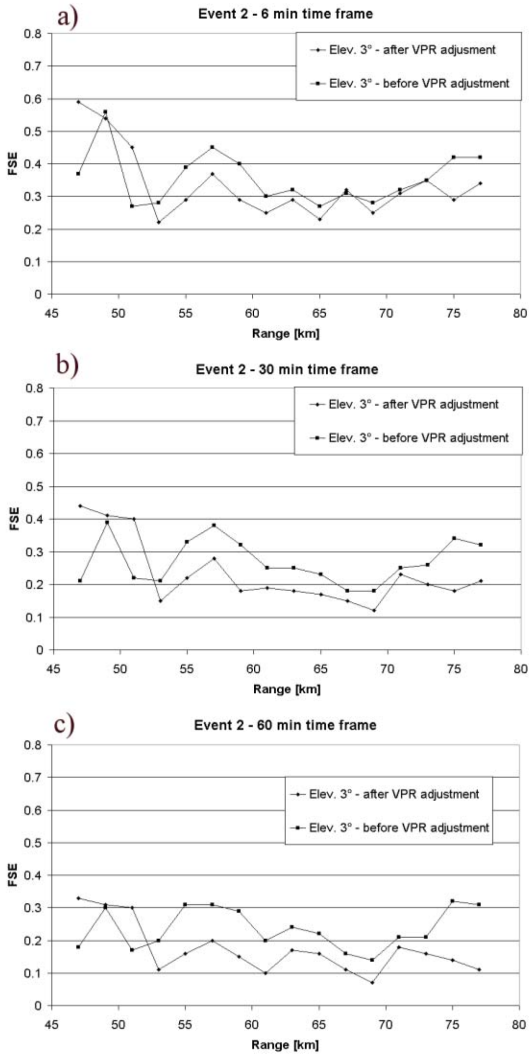

Fig. 5a, b, c: Inter-elevation comparison: *FSE* values between elevations 2.0° and 3.0° before and after *VPR* adjustment (Event 2); a) 6-min time frame; b) 30-min time frame; c) 60-min time frame.

In areas prone (or suspected) to ground effects, it would allow to replace the adjusted estimate from the lowest unobstructed elevation angle by an upper elevation angle free from ground echoes. We have evaluated the inter-elevation statistics, before and after *VPR* adjustment, on the basis of 2.0° and 3.0° scan elevation, essentially because these elevations are almost free (for the studied azimuth ranges) of blocking and ground clutter effects. The reference variable is represented in each case by the lowest elevation (2.0°). Inter-elevation comparisons have been carried out at three different time steps (6 min; 30 min; 60 min) to verify the influence of time accumulation on algorithm performance. As an example, results are reported for Event 2.

Figures 4 to 5a,b,c show *MRE* and *FSE* statistics obtained for the three time frames. Obviously, *MRE* does not change with changing the time frame, and is reported only once.
These results show that the improvements are important both in terms of *MRE* and *FSE*. The significant underestimation which can be noted in Figure 4 for 3.0° scan elevation before adjustment is reduced almost completely; the *MRE* after adjustment ranges between +5% and –5% (with peaks of ± 10%). The correction is homogeneous with range.

Concerning *FSE*, one can note that the errors decrease with increasing the time frame, as expected. This means that for the smallest time frame (6 min) the vertical variability exhibits a significant variability around the average value, represented by the *VPR* structure. At 30 min this variability is filtered out in a significant way, and the *FSE* (both before and after adjustment) is less than 0.4. The *VPR* adjustment is reasonably effective at this time step, and reduces *FSE* (at ranges further than 53 km) by 10-30 %. At 60-min time step *FSE* generally reduces to less than 0.3, and the effectiveness of the adjustment increases (at ranges comprised between 53 and 65 km, *FSE* reduces by 30 to 50%). The adjustment decreases the homogeneity between the two scans at ranges less than 53 km, exactly where the 'nose' of the identified *VPR* (bright-band related) affects the correction. It is likely that the bright band effect is less important for this case study; due to this reason, the correction imposed by using the mean *VPR* is less than effective at these ranges.

The raingauge data collected for each storm event at hourly time step were compared with the radar rainfall estimates aloft, by using radar data from the two elevation scans (2.0° and 3.0°), both before and after *VPR* adjustment. Figures 6a,b and 7a,b show the scatterplot obtained in this way. The figures report also the coefficients of the linear regression of radar values against raingauge measurements. These coefficients and related statistics (slope a , intercept b and correlation coefficient r) are reported also in Table 3.

Tab. 3: Coefficients for linear interpolation of radar-raingauge scatterplots.

Y = aX + b X : raingauge rainfall	*a*	*b*	*r*
Elev. 2°	0.490	0.362	0.698
Elev. 2° VPR adjusted	0.582	0.389	0.698
Elev. 3°	0.432	0.405	0.621
Elev. 3° VPR corrected	0.587	0.363	0.640

Some characteristics are worth noting in Table 3. Value of the slope a decreases from 0.49 at elevation scan 2.0° to 0.43 at elevation 3.0°. This is expected because, as shown above, radar rainfall measures from 3.0° elevation are far prone to underestimation than measures taken at 2.0° elevation. While r statistics doesn't change significantly after *VPR* adjustment, the value of the slope a increases for both elevations. Also, values of a after adjustment are quite similar for both elevations. This means that *VPR* adjustment is effective in reducing both radar-rainfall bias and the heterogeneity between the different scan elevations.
Of course, the scatter plots show clearly that several problems remains in the radar – rainfall estimates, even after *VPR* adjustment. A severe underestimation (in the order of 40%) affect these estimates, whereas isolated cases of overestimation still exist. It is clear that only a more complete and effective understanding of other error sources (and specifically attenuation and hail contamination) may help to increase the representativeness of radar rainfall estimates in this difficult environment.

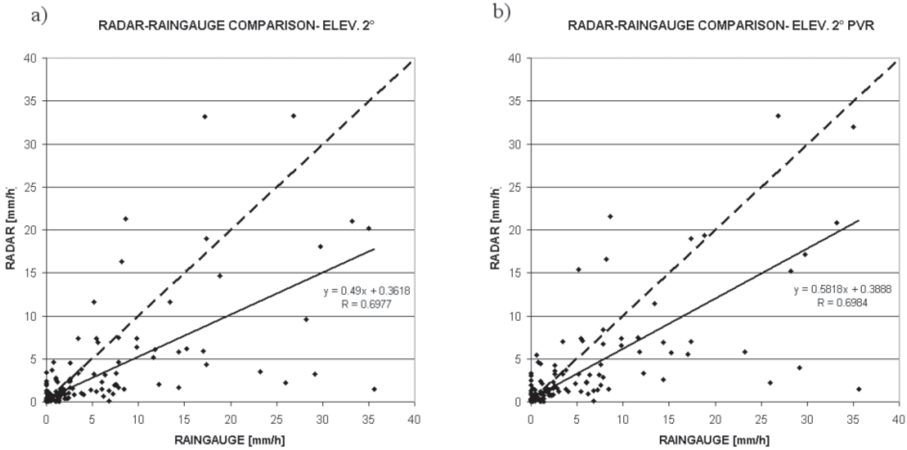

Fig. 6a,b: *Scatterplot of radar-raingauge measurements comparison for all the events. Radar data are taken from elevation 2.0°; a) before VPR adjustment; b) after VPR adjustment.*

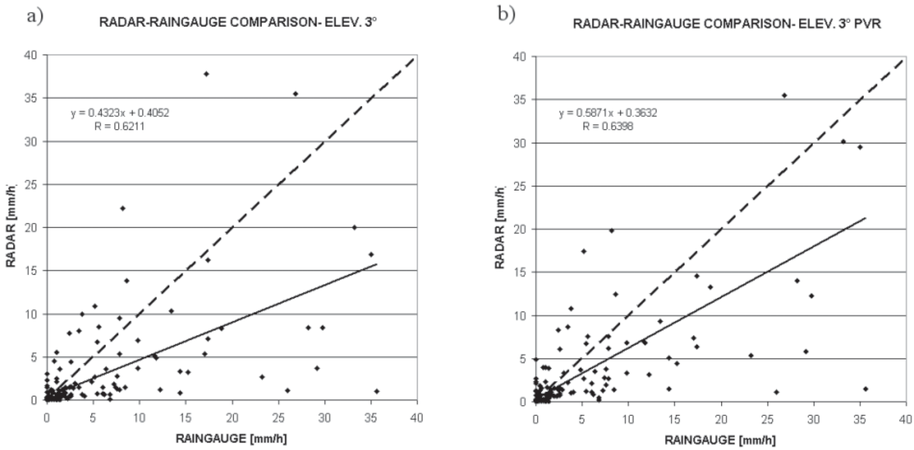

Fig. 7a,b: *Scatterplot of radar-raingauge measurements comparison for all the events. Radar data are taken from elevation 3.0°; a) before VPR adjustment; b) after VPR adjustment.*

CONCLUSIONS

Some major issues that arise in radar rainfall estimation for flood producing storms have been addressed, with specific attention to problems related to the vertical heterogeneity of the reflectivity fields.

The principal conclusions of the paper are summarised below:

- convective storms provide a special challenge for radar rainfall estimation. The vertical profile issues, discussed above, are important elements of the estimation problems. It is also likely that standard *Z-R* parameters are not appropriate for these storms. Baeck and Smith (1998) showed that the microphysical processes involved in low-echo-centroid storms (as those analysed here) may be inconsistent with the nominal *Z-R* relationship used in these analyses.
- Bright band effects play an integral role even in heavy rainfall events. The interplay of storm vertical structure and the increased sampling altitude with range by the M. Macaion radar is an important control of radar rainfall estimates.
- Development and implementation of a simple *VPR* adjustment technique, based on the identification of a mean *VPR* over all the storm events considered, proved to be effective. These results suggest that even a crude estimate of the profile allows us to reduce the vertical heterogeneity of the reflectivity field and the difference between radar- and gauge- estimated rain, even for convective events characterized by high space-time variability of the *VPR* structure.
- Hail and attenuation remain important obstacles for radar based measurement of flood producing storms. Case study analyses show that heavy rainfall and hail occur quite often in the same storm and at the same time. There is also empirical evidence that large hail, high reflectivities, and relatively low rainfall rates occur within a single storm. Attenuation can be important in these cases, as well as when the radar beam cross the melting layer. Additional insight should be gained on these processes in order to develop physically based procedures able to reduce the impact of the relevant error on radar rainfall estimation.

Acknowledgements: This work has been funded by the Commission of the European Communities, DGXII, Framework Programme 6, through Integrated Project '*FLOODsite*'. Ufficio Idrografico di Bolzano (BZ) and Meteotrentino (TN) provided the radar and hydrometeorological data used in this study.

REFERENCES

Andrieu, H., and Creutin, J.D., (1995): "Identification of vertical profiles of radar reflectivities for hydrological applications using an inverse method. Part 1: formulation", *J. Appl. Meteor.*, 34, 225-239.

Austin,P.M., **(**1987**)**: "Relation between measured radar reflectivity and surface rainfall"**,** *Mon. Weather Rev.*, 115,1053-1070.

Baeck, M.L., and Smith, J.A., (1998): "Rainfall estimation by the WSR-88D for heavy rainfall events". *Weather Forecast*., 13, 416-436.

Biggerstaff, M.I., and Listemaa, S.A., (2000): "An improved scheme for convective/stratiform echo classification using radar reflectivity". *J. Appl. Meteor.*, 39, 2129-2150.

Borga, M., and Giaretta, P., (1994): "Errors in beam modeling and correction of partial blocking effects" *Advances in radar hydrology, edited by M.E. Almeida-Teixeria, R.*

Fantechi, R. Moore, V.M. Silva, published by the European Commission, Luxembourg, pp. 105-114.

Borga, M., Anagnostou, E.N., and Frank E., (2000): "On the use of real-time radar rainfall estimates for flood prediction in mountainous basins". *J. Geophys. Res.*, 105, D2, 2269-2280.

Borga, M., Anagnostou, E.N., and Krajewski, W.F., (1997): "A simulation approach for validation of a bright band correction method". *J. Appl. Meteor.*, 36(11), 1507-1518.

Borga, M., Tonelli, F., Moore, R.J., and Andrieu, H., (2002): "Long-term assessment of bias adjustment in radar rainfall estimation". *Water Resour. Res.*, 38(11), 1226, doi:10.1029/2001WR000555.

Creutin, J.D., and Borga, M., (2003): "Radar hydrology modifies the monitoring of flash flood hazard". *Hydrol. Processes*, 17, 7, 1453-1456.

Dinku, T., Anagnostou, E.N., and Borga, M., (2002): "Improving radar-based estimation of rainfall over complex terrain". *J. Appl. Meteor*, 41(12), 1163–1178.

Hardaker, P.J., Holt A.R., and Collier, C.G., (1995): "A melting layer model and its use in correcting for the bright band in single polarization radar echoes", *Quart. J. Roy. Meteor. Soc*., 121, 495-525.

Joss, J., and Pittini, A., (1991): "Real-time estimation of the vertical profile of radar reflectivity to improve the measurement of precipitation in an Alpine region", *J. Meteor. Atm. Phys.*, 47, 61-72.

Joss, J., and Lee, R., (1995): "The application of radar-gauge comparisons to operational precipitation profile corrections", *J. Appl. Meteor*., 34, 2612-2630.

Joss, J., and Waldvogel, A., (1990): "Precipitation measurements and hydrology". *D. Atlas (Ed.), Radar in Meteorology, Amer. Meteor. Society*, 577-606.

Kitchen, M., Brown, R., and Davies, A.G., (1994): "Real time correction of weather radar for the effects of bright band, range and orographic growth in widespread precipitation", *Quart. J. Roy. Meteor. Soc*., 120, 1231-1254.

Krajewski, W.F., and Smith, J.A., (2002): "Radar hydrology: rainfall estimation". *Adv. Water Resour*., 25, 1387-1394.

Smith, C.J., (1986): "The reduction of errors caused by bright band in quantitative rainfall measurements made using radar", *J. Atmos. Ocean. Techn.*, 3, 129-141.

Smith, J.A., Seo, D.J., Baeck, M.L., and Hudlow, M.D., (1996): "An intercomparison study of NEXRAD precipitation estimates". *Water Resour. Res*., 32 (7), 2035-2045.

Steiner, M, Houze, RA, Yuter, SE, (1995): "Climatological characterization of three-dimensional storm structure from operational radar and rain gauge data". *J. Appl. Meteor.*, 34, 1978-2007.

Vignal, B., Andrieu, H., and Creutin, J.D., (1999): "Identification of vertical profiles of reflectivity from volume scan data", *J. Appl. Meteor*., 38, 1214-1228.

Wilson, J.W., and Brandes, E.A., (1979): "Radar measurement of rainfall"**,** *Bull. Amer. Meteorological Soc.,* 60, 1048-1058.