Proceedings of ERAD (2002): 422–427 © Copernicus GmbH 2002

ERAD 2002

Comparing data from radar, rain gauges and a NWP model

M. Gabella[1], **G. Galli**[2], **J. Joss**[3], **and G. Perona**[1]

[1]Politecnico di Torino, Electronics Department, Corso Duca degli Abruzzi, 24, 10129 Turin, Italy
[2]MeteoSchweiz, Locarno Monti, Via ai Monti 146, CH 6605, Switzerland
[3]Intragna, Motto, CH 6655, Switzerland

Abstract. Data from rain gages, radar and a high resolution Numerical Weather Prediction (NWP) model are being analyzed. The accuracy of daily, operational, radar-derived precipitation amounts is verified during heavy rain in the Alps, using in situ measurements (71 gages within 157 km from the radar). Independent data were used for the training and the verification of two adjustment techniques: even a simple bulk-adjustment (based on one correction coefficient, hence, space-independent) leads to a significant improvement; a Weighted Multiple Regression (WMR) is well worth the additional effort of deriving four coefficients to replicate the influences of "calibration", beam-broadening, visibility and orography. Good agreement is found between daily radar/gauges amounts during severe precipitation. This confirms previous findings: in days with "strong" weather signal, the WMR is able to correct several errors in one step ("calibration", beam-broadening, shielding and orographic enhancement). Since it does not require full volume 3D-data, it represents an inexpensive alternative to more sophisticated methods (e.g. reflectivity profile correction). The average forecast (over a $\sim 12\,000$ km^2 area) was in reasonable agreement with the average observations while the intense cells were shifted in space (they were forecast "upstream", while they occurred "upslope").

1 Introduction

The scope of the present study lies within the working area 2 entitled "Approaches to verification" of the Working Group 2 of COST 717 action which is addressing the objective "Using radar observations for parameterisation and validation of atmospheric models" (e.g. Rossa, 2000; Fruhwald, 2000).

Our efforts are towards the use of gauge-adjusted, radar-derived precipitation fields for validation of Numerical Weather Prediction (NWP) models even in regions characterized by a complex orography, where the radar estimations are affected by several sources of error (e.g. Zawadzki, 1984; Koistinen et al., 1999) that are unfortunately particularly severe (e.g. Joss and Waldvogel, 1990; Germann and Joss, 2002). Rain gauges are usually considered to provide accurate point measurements (a description of the main sources of errors affecting "high-resolution" rain gauges can be found, for example, in Nystuen et al. (1996), Nespor and Sevruk (1999), and Duchon and Essenberg (2001). However, for hydrological applications, in which areal precipitation measurements are needed, their main drawback is the areal representativity (Kitchen and Blackall, 1992). Because of the spatial variability of rainfall (especially during intense, convective events), it is obvious that point measurements would lack in representativity even though the measurements themselves were correct. Austin (1987) found that "the spatial variability of rainfall is so pronounced that a single gauge often does not sample representatively over any area, even as small as 4 km^2". Radar measurements may add the desired information on the areal distribution of precipitation. Several studies over the last decades have sought to merge radar estimates with gauge measurements (e.g. Smith and Krajewski, 1991; Ciach and Krajewski, 1999; Seo et al., 2000) to arrive at quantitatively accurate and spatially continuous radar-derived precipitation fields. Many of them analyzed the Radar-to-Gauge ratio (e.g. Cain and Smith, 1976; Koistinen and Puhakka, 1981; Collier et al., 1983) while others applied optimal interpolation techniques (e.g. Krajewski, 1987). Furthermore, probability matching of radar reflectivity and rain rate was introduced on a long-term basis (of the order of a year) by Calheiros and Zawadzki (1987). Earlier, the idea of deriving an Z-R relationship that could differ from a power law, through a comparison in probability, was applied by Drufuca (1977) and by Miller (1972). Subsequently, probability matching was proposed as an adjustment technique during observation periods of about three weeks by Rosenfeld et al. (1993). The method, when applied to stratiform rain in England (Fox et al., 1999), showed promising results.

2 A non-linear Weighted Multiple Regression to derive gauge-adjusted precipitation fields using radar

To cope with problems connected to estimating precipitation with radar in an Alpine context, Gabella et al. (2000) proposed the use of a non-linear Weighted Multiple Regression (WMR). The method seems to be particularly useful to operational services, since it is fast, simple and able to correct several errors in one step and it represents an alternative to more sophisticated methods, which require full volume 3D data (e.g. reflectivity profile correction; a reviewer noted that the Nimrod profile correction at UK MetOffice does not re-

Correspondence to: M. Gabella (gabella@polito.it)

Table 1. Statistical attributes of the network of 71 gauges distributed in a region of about 12 000 km^2 surveyed by the Lema radar: distance from the Swiss Monte Lema radar, D (also on a logarithmic scale, 2nd row), Height of the Gauges above sea level, HG, and minimum Height of Visibility, HV_{min} (it is the minimum height at which a meteorological target must reach to be visible to the radar)

	Mean	Median	Std	Min	Max
D	85 km	81 km	41 km	11 km	157 km
$10 \cdot \log_{10}(D)$	18.6 dB$_{km}$	19.1 dB$_{km}$	2.7 dB$_{km}$	10.5 dB$_{km}$	22.0 dB$_{km}$
HG	760 m	480 m	660 m	80 m	2820 m
HV_{min}	1060 m	650 m	870 m	80 m	2760 m

quire 3D data). In its present form, the WMR method uses the daily Radar-to-Gauge ratio as the response variable and tries to "explain" its variability in space in terms of the following three independent variables: (1) D, the Distance between the radar and the gauges (this being significant as it reflects the altitude of the beam as well as beam broadening and, to some extent, attenuation); (2) HV_{min}, the minimum Height a meteorological target must reach over the gauge-pixel to be Visible to the radar, taking consideration of shielding effect (it reflects the influences of the vertical profile of reflectivity); (3) HG, the Height of the Gauge (corresponding to the altitude of the terrain; this reflects the depth of the layer where precipitation growth related to orography can occur). These effects, together with the vertical profile of reflectivity, lead to biases: usually a relevant underestimation of rainfall by radar at longer ranges and at larger HVmin, and a small under- or over-estimation associated to HG, depending on whether growth or evaporation is dominant. Note that the vertical profile of reflectivity also includes the influence of the bright band and of the water- and ice-phases. The variability of the daily Radar-to-Gauge, AF is analyzed on a decibel scale. For each radar-gauge data couple, the adopted multiple linear regression is written as

$$\boldsymbol{AF}(dB)_{est} = 10 \cdot \log(\boldsymbol{AF})_{est} = a_0 + a_D \cdot \log(\boldsymbol{D}) + a_{HV} \cdot \boldsymbol{HV}_{min} + a_{HG} \cdot \boldsymbol{HG} \quad (1)$$

the components of the vectors being $AF_j = (R_t/G_t)_j$, D_j, HV_j, and HG_j, where j identifies the j^{th} radar-gauge couple. Instead of an ordinary multiple regression, a weighted multiple regression should be used to better correct the radar estimates. Gabella et al. (2001) showed that the best results are obtained when the observations are *weighted* with the radar-derived precipitation values. In Sect. 4 of Gabella et al. (2001), a more detailed description of the method is presented.

3 Geographic, instrumentation and data description

The digital elevation map in Fig. 1 shows the area of the experiment, which is located in Northwest Italy within the

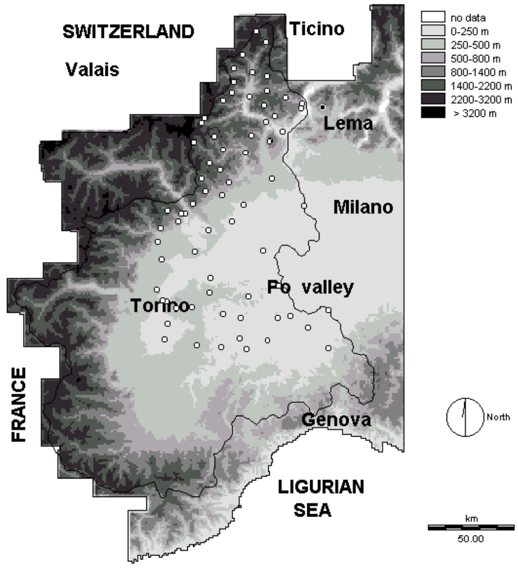

Fig. 1. Digital Elevation map of the northwestern part of Italy, political boundaries of Piedmont (black line), principal places mentioned in the text, *Monte Lema* radar site (black mark) and location (white marks) of the 71 rain gauges used in the quantitative analysis presented in Sect. 6 and Table 2.

Piedmont region (whose political boundaries are indicated with a black line). Due to the high differences in level, air masses directed towards the northwest and coming from the south and east are subject to sudden upward motions. Adiabatic expansion causes condensation and precipitation: the northern and western parts of Piedmont are subject to heavy and frequent rainfalls. The recurrence of hydrogeologic disasters at the foot of the Alps is well known. For example, 642 mm of rain were recorded in three consecutive days in 1945. The white marks in Fig. 1 indicate the 71 rain gauges (tipping-bucket with 0.2 mm resolution) within the selected area of interest (a region of approximately 12 000 km^2 shown in Figs. 2, 3 and 4). The rather asymmetrical distribution of the gauge altitudes is summarized in the 3rd row of Table 1. The Swiss C-band radar is located on the top of Monte Lema at 1625 m a.s.l. (solid mark in the upper right part of Fig. 1). The statistical characteristics of the distances between the Monte Lema radar and the gauges are summarized in the first row of Table 1. Since the logarithm of the distance, D, and the minimum height a meteorological target must reach to be visible to the radar, HVmin, are used as input in the correction scheme based on the WMR, their statistical characteristics are also shown in Table 1. A computer code for radar site assessment (Gabella and Perona, 1998) has been used to compute HV_{min}. The equivalent-earth's-radius used is 8500 km.

The Monte Lema radar is a C-band Doppler radar. The full volume is scanned with a 1° beam at 20 elevations. The clutter-free range bins of $1° \times 1° \times 80$ m are averaged and resampled on a Cartesian grid. An "OVERVIEW" product, containing full volume reflectivity information, is updated every 5 min. It consists of 12 CAPPI images corresponding to the 1–12 km above sea level heights and one projection containing the maximum vertical reflectivity. For each day, 288 of these maximum reflectivity maps were converted to precipitation rates using a power-law $Z-R$ relationship with $b=1.5$ and $a=316$ ($Z=aR^b$).

4 Event description with focus on rainfall amounts

A factor that characterised the "13–15 October 2000" heavy rain period was its quasi-steadiness. This was caused by the presence of an anticyclone over Eastern Europe.

The high level trough centered over the Iberian Peninsula produced on 13 October a moist and warm flow running over Northern Italy. At the same time the surface situation was characterized by a not very deep pressure minimum, which, however, spread over the entire Western Mediterranean. This is one of the factors that led to a considerable introduction of moisture into the atmosphere. Precipitation was intense: the **mean daily** precipitation measured by the 71 gauges was **63.8 mm** (with a maximum of 402 mm); the median was 29.8 mm. The twice-a-day radio soundings available from Milano Linate ($\approx$ 70 km southeast of the Lema radar) show quasi-standard decreases of refractivity in the lower atmosphere for the whole 3-day period. On 13 October they measured a zero isotherm height of 3000 and 3400 m (00:00 and 12:00 UTC).

On 14 October, the high-level pattern was determined by the cut-off of the trough and, correspondingly, two surface pressure minima were observed: the first was that which had already been present on 13 October, and which was now localized over the Northern Mediterranean; the second one was associated to the high-level cut-off, and was centered over Tunisia. During the day, this second minimum moved towards the Northern Mediterranean and deepened because of a latent-heat exchange with the sea. The new location of this minimum generated strong easterly currents at low levels, and also caused the transport of moisture from the Adriatic Sea. This flow produced widespread precipitation over the entire Piedmont, with the strongest precipitation associated with orographic lifting. Precipitation was again intense: the **daily** rain-gauge **average** was **73.8 mm** (with a maximum of 225 mm); the median was 50.6 mm. The measured zero isotherm height was at 3550 and 3000 m, values considerably larger than the normal October amounts (as in the previous day).

During 15 October, the closed cyclonic circulation moved towards Northern Europe and its new location was centered over the Pyrenean chain. The low deepened further because of the transit over the Mediterranean Sea. This new configuration caused (especially in the second half of the day) an injection of cold air over Northern Italy, and produced an over-saturation of the moisture that was already present in the atmosphere and subsequent destabilization. 15 October is characterized by an extreme value of **mean daily** precipitation: **118.2 mm**. Given the number of gauges (71) and the size of the area where they were located ($\sim$12 000 km^2), it is even more unusual that this mean value was smaller than the median (123.6 mm). Daily maximum was 240 mm. The measured zero isotherm height decreased initially slowly (from 3400 m at 00:00 UTC to 3200 m at 12:00 UTC), and then rapidly (2400 m at 00:00 UTC, 16 October).

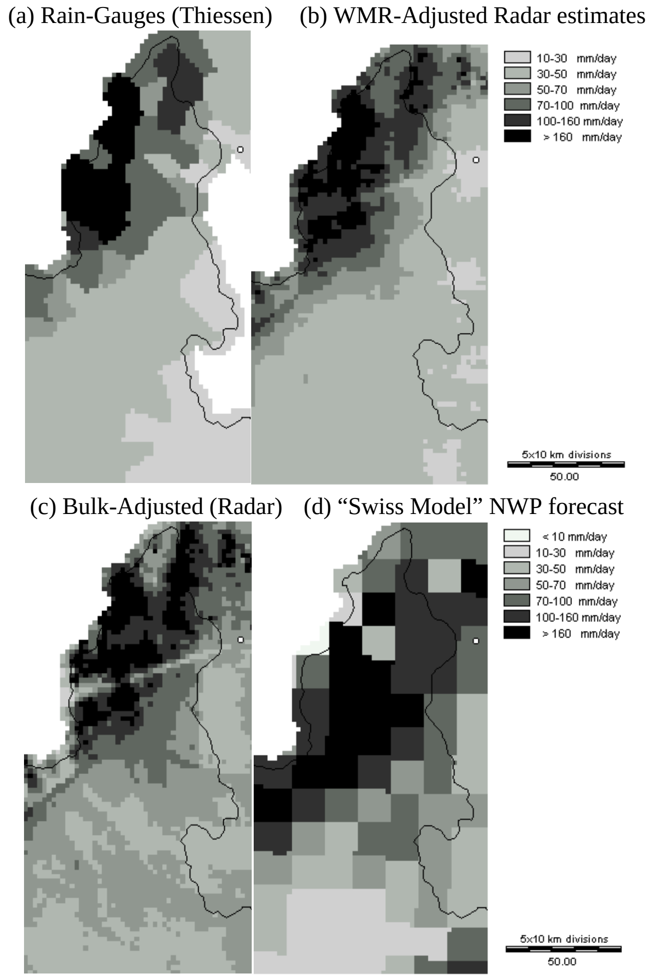

Fig. 2. Spatial distribution of 14 October daily precipitation: (a) in situ point measurements represented using the Thiessen (1911) scheme; (b) and (c) adjusted radar estimates represented on a 2 $\times$ 2 km^2 Cartesian grid (based on 288 temporal samples of maximum reflectivity echoes along the vertical); (d) "Swiss Model" Numerical Weather Prediction forecast (approximately 14 $\times$ 14 km^2 spatial resolution) on 14 October (00:00 UTC + 24 h).

The first day of the event was used for training the adjustment coefficient(s) (Sect. 5), then the next two days were used for the verification (Sect. 6).

5 Training the bulk- and WMR-adjustment techniques

It is not surprising that in a "hostile" environment (i.e. mountainous), radar precipitation estimates derived using a single $Z-R$ relationship result in a large underestimation. The radar underestimation is the effect of a decreasing vertical

Table 2. Average precipitation over the selected area of about 12 000 km^2. These **daily amounts** are measured in mm and refer to 71 in situ measurements (rain gauges), 71 remotely-sensed estimates (radar) above the gauges, about 3000 radar-adjusted estimates and 98 Swiss Model NWP pixels over the whole monitored region

	Gauges	Radar bulk-adjust. Above gauges	Radar bulk-adjust. Whole region	Radar WMR-adjust. Above gauges	Radar WMR-adjust. Whole region	NWP Whole region
14 Oct	73.8	87.9	80.5	82.5	74.8	80.8
15 Oct	118.2	101.4	100.1	96.0	95.1	87.6

profile of reflectivity with height combined with beam shielding and/or occultation by relief. One of the simplest remedy that can be used to compensate this bias is the so-called bulk adjustment. It consists of multiplying radar precipitation estimates by the ratio between the Gauges- and Radar-total (overall total, in time and space). For instance, for the "training day" (13 October), an amplification factor equal to 2.3 is obtained by dividing the total daily Gauge/Radar amounts (71 gauges in the northeastern Piedmont, $\sim 12\,000$ km^2). Using the radar derived precipitation values as weights, the following values of the Weighted Multiple Regression coefficients (1) are obtained (D, HV_{min}, and HG are expressed in km):

$$\boldsymbol{AF}(dB)_{est} = 3.9 - 3.3 \cdot \log(\boldsymbol{D}) - 1.2 \cdot HV_{min} + 0.4 \cdot \boldsymbol{HG} \quad (2)$$

The bulk adjustment technique would be equivalent to the WMR-adjustment, if all the coefficient but a_0 in the above equation were zero. However, this is not the case: hence, with the WMR method, radar estimates are not equally amplified over the whole region; instead, each radar pixel receives a correction factor that is a function of the distance from the radar, the minimum height of visibility and the height of the terrain. The values of the coefficients are somehow artificial, since they depend on the units used in the regression (the distances from the radar are measured in kilometers) and on the reference system (the heights refer to the mean sea level and are also measured in kilometers). Furthermore, the regression coefficients should be applied only within the range they were determined (e.g. distances between 10 and 160 km).

As expected, both coefficients a_{HV} and a_D are negative, indicating that the radar underestimates precipitation for higher sampling volumes and longer distances. On the contrary, a_{HG} is positive and its contribution in explaining the variability of AF is not negligible. It is worth noting that better results are found using HV_{min} and HG separately in the WMR equation, rather than as the difference between the two.

6 Verification and results

Both the bulk- and the WMR-adjusted mean amounts of rainfall amounts are rather overestimated for 14 October (see Table 2 for a summary of the mean precipitation amounts). From a quantitative point of view, the WMR offers a better agreement not only for the residual bias, but also in terms of **standard deviation** of the **daily** radar-gauge **differences** at each site: **37.6 mm** (WMR) versus **39.9 mm** (bulk-adjustment). The great deal of effort that was made in the attempt to transform **quantitative** radar estimates of precipitation in mountainous terrain from the "research ivory tower" to operational meteorological services, should not make us forget the main advantages of radar: to provide a three-dimensional **qualitative** overview on the weather and show, in real-time, **where** and **when** something is happening. The qualitative point of view (i.e. a visual inspection of daily precipitation fields) can also be important. Figure 2 shows for the sake of comparison both the observations (from in situ and remotely sensed measurements) and the forecasts. The upper-left picture shows the spatial distribution of precipitation over the study area, derived from a limited number of point measurements (gauges outside Piedmont have also been used to derive this picture, that is, 2 in the Eastern part of Valle d'Aosta, 2 in the Southeastern part of Valais and 8 in Ticino) using a very simple technique proposed many years ago (Thiessen, 1911). Thiessen devised a simple interpolation scheme that assigns the amount recorded by the nearest gauge to every unit grid area of the domain of interest. The result is a pattern of polygons (also known as Voronoi tesselation) that outlines the area of influence of each gauge, creating rather artificial boundaries of abrupt rainfall gradients that are dictated by the rain gauges' spatial distribution. The upper right and lower left pictures show the radar-derived daily amounts: the former refer to the WMR-adjustment the latter to the simple bulk-adjustment. A qualitative, visual comparison with the point measurements, confirms the results of the quantitative analysis: the WMR-adjustment performs better than a simple bulk-adjustment. Note how, in the bulk-adjusted image, there are no pixels with amounts between 10 and 30 mm, while some gauges in the Southeast measured such amounts.

Finally, the lower-right picture shows the forecasts from the Swiss Model (SM) on 13 October, at 00:00 UTC + 24 h + 48 h (i.e. the "previous-day midnight-forecast" accumulated over the next 24 up to 48 hours successively). The reference grid is a latitude/longitude reference systems (the grid mesh is about 14 km). The shape of the pixels reflects the conversion from lat/long to the conformal Swiss cartographic kilometric reference system using a nearest-neighbor resampling procedure. The Swiss Model (SM) is a hydrostatic meso-"beta" scale numerical weather prediction model operationally used at the MeteoSwiss in 1994–2000. It has been developed in a joint effort by the Deutscher Wetterdienst (DWD) and MeteoSwiss as a high-end resolution version of the Europa Modell of the DWD (Majewski, 1991). In a slightly different configuration the same model was opera-

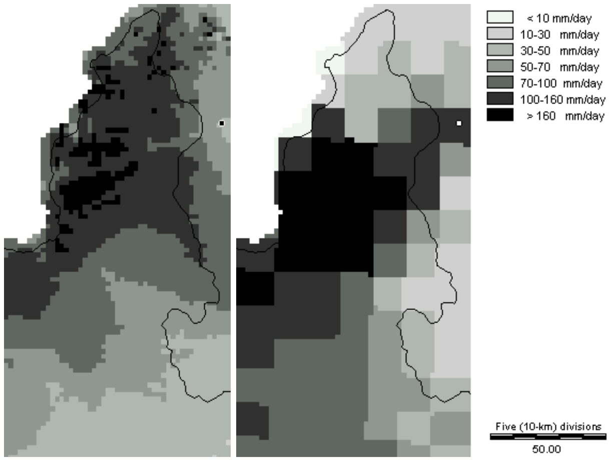

Fig. 3. Spatial distribution of 15 October daily precipitation. Left: adjusted radar estimates using a Weighted Multiple Regression represented on a 2 $\times$ 2 km^2 Cartesian grid. Right: "Swiss Model" Numerical Weather Prediction forecast on 15 October (00:00 UTC + 24 h). None of the rain gauges (as well as none of the radar pixels) measured less than 10 mm/day; on the contrary, several NWP pixels forecasted such a underestimated value.

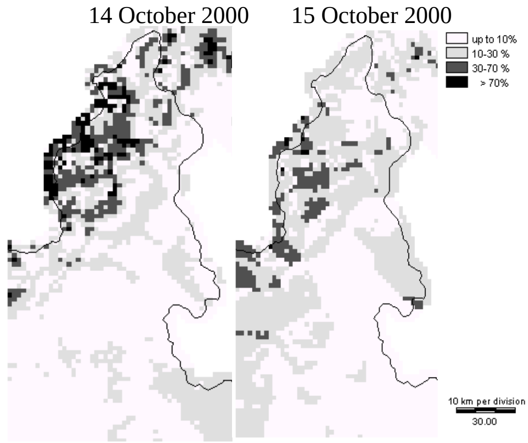

Fig. 4. Normalized daily errors associated to daily radar estimates of precipitation using a Cartesian, operational, maximum reflectivity echo product. Four error categories have been defined: "acceptable" (< 10%), "poor" (between 10% and 30%), "very poor" (between 30% and 70%) and "qualitative" (larger than 70%). The mean precipitation amounts measured by 71 gauges were 73.8 mm (14 October) and 118.2 mm (15 October). The two pictures clearly shows that the Lema radar estimates have proved to be accurate in the flat and hilly Eastern part of Piedmont. Operational radar estimates behind and over the Alps can only be of qualitative use.

tional at DWD till end of 1999 under the name Deutschland Modell (DM). The **mean forecasted-precipitation** over the area was **80 mm**.

Four pixels show a forecast that is smaller than the minimum observed (10 mm/day). In short, it can be said that reasonable agreement is found in the average intensity between the observed/forecast-precipitation, while from Fig. 2, it is evident that the position of the NWP-precipitation-forecast was shifted in space. The forecast failed to position the embedded convection cells so deep within the Alpine chain.

The adjustment for 15 October gives a mean daily radar underestimation compared to gauges for both the bulk and WMR technique. The standard deviation of the "errors" (daily differences between gauge and radar amounts), as well as a qualitative visual inspection of the corresponding radar-derived precipitation fields, again show that the WMR-adjustment is better than a simple bulk-adjustment (just like in Fig. 2). The WMR-adjusted, radar-derived precipitation fields are shown in Fig. 3 for comparison with the daily forecasts. It is possible again to observe a misplacement of the rainfall peaks and a large area of disagreement in the flatlands (southeastern part of the image). Patches of even larger disagreement are evident at the boundary between Piedmont and Switzerland. On 14 October, the mean forecast was in reasonable agreement with the observations, but the intense cells were shifted in space (they were forecast "upstream", while they occurred "upslope"). On 15 October (a day of extreme precipitation), the NWP was not even able to predict the average amount (Table 2). Many pixels show a forecast that is smaller than the minimum observed (30 mm/day) and, as for 14 October, there is a false alarm of heavy precipitation next to the *Lema* radar.

7 Uncertainties

Since the first attempts to use radar to quantitatively estimate precipitation, a debate has arisen concerning the accuracy needed for hydrological applications. In recent years more and more experts have agreed that radar can be useful, even with poor accuracy, as long as an uncertainty map accompanying the radar estimates can be provided. Although several attempts have been made to quantify the errors associated with radar estimates of precipitation, we are still far from having a complete error map that provides the corresponding uncertainty for each pixel, in time and space, and for each type of operational product.

As a further contribution in this direction, we present error maps (Fig. 4) for the precipitation fields derived from "maximum radar reflectivity". The two error images shown in Fig. 4 refer to 14 and 15 October and have been obtained as the differences between WMR-adjusted radar-derived rain fields and gauge hysohyets (in fact square-distance weighting function). Since they have been obtained simply as the difference between the radar (WMR-adjusted) and the gauge-derived precipitation fields, their main disadvantage is that they are deterministic. However, they confirm quantitatively that during both days of severe precipitation the *Lema* radar estimates have proved to be accurate in the (flat and hilly) Eastern part of Piedmont (i.e. south of the Alpine chain). Operational radar estimates behind and over the Alps, eventhough adjusted, can only be of qualitative use.

8 Summary and conclusions

As in previous rainfall events, radar precipitation estimates derived from the Monte Lema Doppler radar, which operates in a mountainous terrain, are considerably underestimated. During three days of the October 2000 Piedmont flood, the daily overall Gauge-to-Radar ratio (mean precipitation measured by 71 gages within 157 km from the radar in $\sim 12\,000$ km^2 area divided by the mean value of the corresponding radar estimates aloft) is equal to 2.3, 1.9 and 2.7, respectively. It is evident that even a simple bulk-adjustment (e.g. trained during the first day and applied during the following days of the event) leads to a significant reduction of the bias. As in previous studies, better results can be obtained using a Weighted Multiple Regression (WMR) adjustment scheme, which, by means of 4 coefficients tries to reduce errors associated with problems of "calibration", beam-broadening and homogeneous beam filling, visibility and orography. The WMR-method can also be useful as a diagnostic tool: in fact, if we were able to correct the radar data for all sources of error, then we would find no correlation whatsoever between the Radar-to-Gauge ratio, on the one hand, and the three explanatory variables, on the other hand.

According to the recommendations of the Working Group 2 of the COST 717 action (within the framework of the "Approaches to verification" working area), the daily WMR-adjusted radar-derived precipitation fields are compared with NWP forecasts: we find that the intense cells are shifted in space (they were forecast "upstream", while they occurred "upslope"). The average areal ($\sim 12\,000$ km^2) precipitation forecasts are in reasonable agreement with observations on 14 October, but not on 15 October.

Acknowledgement. We would like to thank Francis Schubiger (MeteoSchweiz) for the "Swiss Model" NWP forecasts. Gauges data were provided by Regione Piemonte.

References

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

Cain, D.E., and Smith, P.L., Operational adjustment of radar estimated rainfall with rain gauge data: a statistical evaluation, Preprints 17th Conf. on Radar Meteorology, Seattle, WA, Amer. Meteor. Soc., 533- 538, 1976.

Calheiros, R.V., and Zawadzki, I., Reflectivity-Rain rate relationships for radar hydrology in Brazil, J. Appl. Meteorol., 26, 118-132, 1987.

Ciach, G.J., and Krajewski, W.F., Conceptualization of radar-rain gauge comparisons under observational uncertainties, J. Appl. Meteorol., 38, 1519-1525, 1999.

Collier, C.G., Larke, P., and May, B., A weather radar correction procedure for real-time estimation of surface rainfall, Q. J. R. Meteorol. Soc., 109, 589-608, 1983.

Duchon, C.E., and Essenberg, G.R., Comparative rainfall observations from pit and aboveground rain gauges with and without wind shileds, 37, 3253-3263, 2001.

Drufuca, G., Radar derived statistics on the structure of precipitation patterns, J. Appl. Meteorol., 14, 1419-1429, 1977.

Fox, N.I., Collier, C.G., Tillford, K.A., Melbourne, P., and Hetherington, D., Rain gauge adjustment of radar measurements of stratiform rainfall, Preprints, 29th Conf. on Radar Meteorology, Montreal, Canada, Amer. Meteor. Soc., 840-843, 1999.

Frhwald, Using radar observation for parameterisations and validation of atmospheric models. Strategy of COST 717 working group 2 , Phys. Chem. Earth (B), 25, 1251-1256, 2000.

Gabella, M., and Perona G., Simulation of the orographic influence on weather radar using a -geometric-optics approach, J. Atmos. Oceanic Technol., 15, 1486-1495, 1998.

Gabella, M., Joss, J., and Perona, G., Optimizing quantitative precipitation estimates using a non-coherent and a coherent radar operating on the same area, J. Geophys. Res., 105, 2237-2245, 2000.

Gabella, M., Joss, J., Perona, G., and Galli, G., Accuracy of rainfall estimates by two radars in the same Alpine environment using gauge adjustment, J. Geophys. Res., 106, 5139-5150, 2001.

Germann, U., and Joss, J., Operational measurement of precipitation in mountainous terrain, this issue, 2002.

Joss, J., and Waldvogel, A., Precipitation measurements and hydrology. A review. Radar Meteorology, D. Atlas, Ed., Amer. Meteor Soc., Boston, Chapter 29a, 577-606, 1990.

Kitchen, M., and Blackall, R.M., Representativeness errors in comparisons between radar and gauge measurements of rainfall, J. Hydrol., 134, 13-33, 1992.

Koistinen, J., and Puhakka, T., An improved spatial gauge-radar adjustment technique, Preprints, 20th Conf on Radar Meteorology, Amer. Meteor. Soc., 179-186, 1981.

Koistinen, J., King, R., Saltikoff, E., and Harju, A., Monitoring and assessment of systematic measurement errors in the NORDRAD network, Preprints, 29th Conf. on Radar Meteorology, Montreal, Canada, Amer. Meteor. Soc., 765-768, 1999.

Krajewski, W.F., Cokriging of radar-rainfall and rain gauge data, J. Geophys. Res., 92, 9571-9580, 1987.

Majewski, D., The Europa Modell of the Deutscher Wetterdienst. ECMWF Seminar on numerical methods in atmospheric models, Vol.2, 147-191, 1991.

Miller, J.R., A climatological Z-R relationship for convective storms in northern Great Plains, Preprints, 15th Radar Meteor. Conference, AMS, Boston, Mass., 153-154, 1972.

Nepor, V., and Sevruk, B., Estimation of wind-induced error of rainfall gauge measurements using a numerical solution, J. Atmos. Oceanic Technol., 16, 450-464, 1999.

Nystuen, J.A., Proni, J.R., Black, P.G., and Wilkerson, J.C., A comparison of automated rain gauges, J. Atmos. Oceanic Technol., 62-73, 1996.

Rossa, A.M., COST 717 Use of radar observations in hydrological and Numerical Weather Predcition models, Phys. Chem. Earth (B), 25, 1221-1224, 2000.

Rosenfeld, D., Wolff, D.B., and Atlas, D., General probability-matched relations between radar reflectivity and rain rate, J. Appl. Meteorol., 32, 50-72, 1993.

Seo, D.J., Breidenbach, J.P., Fulton, R., Miller, D., and O'Banon, T., Real time adjustment of range dependent biases in WSR-88D rainfall estimates due to non-uniform vertical profile of refractivity, J. of Hydrometeorology, 1, 222-224, 2000.

Smith, J.A., and Krajewsky, W.F., Estimation of the mean field bias of radar rainfall estimates, J. Appl. Meteorol., 30, 397-412, 1991.

Thiessen, A.H., Precipitation averages for large areas, Mon. Weather Rev., 39, 1082-1084, 1911.

Zawadzki, I., Factors affecting the precision of radar measurements of rain, Preprints, 22th Conf. on Radar Meteorology, Zurich, Switzerland, Amer. Meteor. Soc., 251-256, 1984.