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Weather dependent training and large sample evaluation of quantitative precipitation estimation by radar

M. Gabella[1], M. Bolliger[2], G. Galli[2], U. Germann[2], A. Rossa[3], and G. Perona[1]

[1]Dipartimento di Elettronica, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy
[2]MeteoSchweiz, Locarno Monti, Via ai Monti 146, CH 6605, Switzerland
[3]MeteoSchweiz, Zurich, Switzerland

Abstract. Quantitative precipitation estimation in complex terrain is a challenge. Many papers have been published on the use of radar measurements to estimate surface rainfall during intense events of a few days, but only little work has been dedicated to large data sets spanning several months and tens of thousands of km^2. This paper presents the analysis of two years of radar and gauge data of whole Switzerland. The analysis is based on the operational radar product RAIN, which combines radar measurements from 20 elevations. Resolution is 5 min and 1 km. Data processing includes automatic calibration, 7-step clutter elimination, correction for partial shielding and profile effects. Comparison of RAIN with measurements of 442 gauges (2-year average ∼3000 mm) shows a root mean square of Differences of ∼1700 mm. This figure refers to the whole Swiss territory (41 000 km^2) including the mountainous areas with bad radar visibility. A space-independent bulk-adjustment reduces it to ∼900 mm. A space-dependent computational model for adjusting radar precipitation estimates based on a non-linear Weighted Multiple Regression (WMR) shows a further reduction to 675 mm. The 730 days are then grouped into 8 weather classes according to the Alpine Weather Statistics and weather dependencies are analyzed. Again the WMR technique shows the best performances.

1 Introduction

For more than five decades researchers have been trying to quantitatively assess rainfall amounts at the ground using radar echoes aloft. Literature is full of (intense) precipitation events observed by radar (several hours; several thousands of square kilometers).

Analysis of larger datasets (weeks, months or even years) over spatial scales (tens of thousands of square kilometers) involving a network of radars are certainly much more unusual. This paper presents the results of an analysis of 2-year data from the MeteoSwiss network of C-band Doppler radars. A quantitative estimation of rainfall amount from radar requires a suitable interpretation of the measured radar reflectivity, Z, to the rain rate, R, possibly at the ground surface and not aloft, as observed by the radar. It is well known that spatial and temporal variability of raindrop size distribution within the radar cell, water- and ice-phase negatively affect the quality of the radar estimates. A negative effect is often played by non-uniform beam filling (the radar cell volume increases with the square of the distance from the radar). However, in mountainous terrain, and in particular in the Alps, the major problem is certainly "radar visibility" under normal propagation conditions, i.e. height at which a storm must reach to be visible to the radar not only because the equivalent-earth-curvature, but most of all shielding by mountains (including the variability of the vertical profile of radar reflectivity). Comparing radar observations with in situ point measurements in mountainous terrain is a challenge and require to cope with these problems (the literature on this topic is abundant see e.g. Gjertsen et al. (2003 and references therein).

A well-known technique that has been used in Europe to combine radar and gauge data, particularly in complex orography regions, is that of a non-linear Weighted Multiple Regression (Gabella et al., 2001), which was developed in cooperation with radar-meteorologists from the Swiss Confederation and the Czech and Slovak Republics (Boscacci, 1999; Kracmar et al., 1999; Gabella et al., 1999) and successfully applied to the most (severe/extreme) events that occurred in the 1994–2001 period on the southern side of the Western Alps (Gabella, 2004). Here, it is applied to the "large" 2-year long MeteoSchweiz dataset.

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

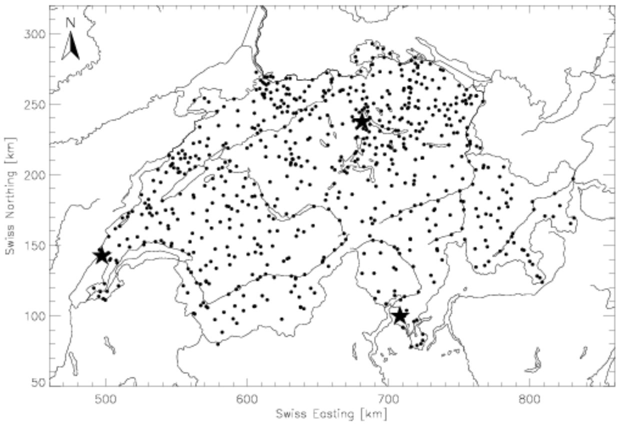

Fig. 1. Conformal map of Switzerland, network of 3 C-band radars (black stars) and of 442 rain gauges (small dots). The Cartesian axes show the Swiss National (kilometric) coordinates.

Table 1. Statistical characteristics of the 442 radar-gauge couples in Switzerland: Height of the Gauges above sea level, HG; Height of Visibility above the Gauges, HV (i.e. height a weather target must reach to be visible from the radar site); Distances between the radar and the gauges, D; logarithm of the Distances normalized to 1 km (same logarithmic dimension used in the non-linear Weighted Multiple Regressions).

	Mean	Median	Std	min	Max
D	67 km	62 km	34 km	1 km	155 km
Log10(D)	1.75	1.79	0.3	0.04	2.19
HG	0.85 km	0.73 km	0.46 km	0.20 km	3.32 km
HVmin	1.95 km	1.48 km	1.25 km	0.51 km	5.64 km

2 Geographic, instrumentation and data description

This study is based on 24 months (from December 2000 to November 2002) of data obtained from the MeteoSwiss C-band radar network and a very dense network of rain gauges (442 in situ daily observations over ~41 000 km^2). Figure 1 shows a map of Switzerland projected onto the conformal Swiss cartographic reference system[1], the 442 rain gauge (small dots) and 3 radar locations (stars).

The MeteoSwiss radar network consists of three C-band Doppler radars. The radar sites are: Albis (681 E, 238 N), near Zurich; Dole (497 E, 142 N), near Geneve ; and Lema (708 E, 100 N). Each radar scans the full volume with a 1° beam at 20 elevations. The $1^\circ\times1^\circ\times80$ m clutter-free range bins are averaged and re-sampled on a Cartesian grid. An "OVERVIEW" product that contains full volume reflectivity information, is updated every 5 min. It is well known that it is not sufficient to simply take reflectivity aloft and then use some Z-R relations to derive the rainfall rate on the ground. MeteoSwiss has in fact been working hard in recent years to improve the operational radar estimation of precipitation. These efforts have led to the RAIN product, in which the "best" estimate of precipitation at ground level is retrieved through a weighted mean of all the radar observations aloft. The weighting function is derived from an average vertical profile of radar reflectivity observed within 35 km from the radar. A maximum of 288 "RAIN" maps were used each day to derive the collocated radar amounts above the gauges: the raw data were converted into precipitation intensities using a power-law Z-R relationship ($Z = aR^b$) with b=1.5 and a=316. A detailed description of the radars can be found on the MeteoSwiss Website, while a detailed characterization of the hostile orography can be found in Germann and Joss (2004). In this paper, the radar-gauge comparison involves one radar (out of 3) which has the best ("lowest") Height of Visibility, HV. The distribution of the radar-gauge distance (also on the logarithmic scale used in the regression) and the HV, according to this criterion, is shown in Table 1 (the equivalent-earth's-radius that is used is 8000 km). Table 1 also shows the Height of the Ground, HG, which is used together with HV and Log(D) as an explanatory variable in the Weighted Multiple Regression.

3 Methods

To cope with problems connected to estimating precipitation with radar in an Alpine context, Gabella et al. (2001) 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. A detailed description of the method is in Sect. 4 of Gabella et al. (2001). In brief, the WMR tries to "explain" the spatial variability of the ratio between radar and rain gauges (this Factor, F_{dB}, is represented on a logarithmic decibel scale) using the following three variables: (1) D, the Distance between the radar and the gauges (reflecting beam broadening, non-uniform beam filling as well as the altitude of the beam); (2) HV, the Height a meteorological target must reach to be Visible to the radar (reflecting beam shielding and vertical profile of reflectivity); (3) HG, the Height of the Gauge (reflecting orography):

$$\boldsymbol{F}_{dB} = a_0 + a_D \cdot Log\,(\boldsymbol{D}) + a_{HV} \cdot \boldsymbol{HV} + a_{HG} \cdot \boldsymbol{HG} \qquad (1)$$

So far, the *a posteriori* verification was based on two independent, mutually exclusive subsets of radar-gauge couples (the N couples were divided into two subsets of $N/2$ elements by selecting and splitting couples of nearest-neighbors; when the 1st one was used for training the coefficients, the 2nd one was used for the verification and vice versa; we got two sets of WMR-coefficients based on $N/2$

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[1] The Swiss National Coordinates result from a conformal mapping (true angles) from the earth surface on a cylindrical surface. The earth surface is approximated by a Bessel's ellipsoid whose normal is coincident with the Geoid vertical in Bern. The ellipsoid is then "transformed" on a non-transverse cylindrical surface which is tangential in Bern (where the kilometric grid is set to the reference "origin" coordinates of 600E, 200N).

Table 2. Statistics of two-year precipitation amounts (in mm) over Switzerland, as sampled by 442 Gauges and Radar echoes aloft. Spread is defined as half the difference between the 16% and 84% percentiles.

	Mean	Median	16%	84%	St. dev	Spread
R(adar) raw	1445	1351	597	2109	862	756
Gauges	3008	2884	2301	3808	807	754
R WMR-adj.	2821	2484	1747	3776	1479	1015

couples). Here, we also use a cross-validation approach: the idea is to exclude one observation at a time when deriving the coefficients, and then use these coefficients to predict the excluded data point (we get therefore N sets of coefficients based on $N-1$ couples).

4 Radar-derived precipitation fields analysis

Table 2 summarizes the statistical characteristics of 2-year precipitation amounts over Switzerland, measured in 442 “points” at the ground (by the gauges) and aloft (by the radar). The first line refers to the RAIN product (see Sect. 2) in its “raw” format. If we compare the average value with the Gauges one (2nd line) we find a (“bulk”) underestimation of a factor of ∼2 (this comparison includes the mountainous areas with bad radar visibility). In a complex-orography environment, beam shielding, partial beam occultation and “overshooting” (the beam volume in snow is often larger than in rain!) cause large radar under-estimations of precipitation. This kind of under-estimating sampling bias is accentuated in environments which enhance the sampling difference between the precipitation at the surface and the radar estimate aloft, i.e. in the relatively cold climate of Canada (Zawadzki 1984) and Finland (Koistinen and Puhakka 1986) as well as in the temperate climate of Switzerland (Joss and Waldvogel 1990), where the heavy shielding by mountains forces the radar beam to hit the snow at the higher elevation scans.

The top picture in Fig. 2 shows a two-year map of precipitation as derived from the MeteoSwiss network of radars using the operational “RAIN” product multiplied by the bulk-adjustment factor (3008/1445). The bottom picture shows a WMR-adjusted map (see Eq. 2). A linear intensity scale (with 4 levels of gray) has been applied: the width of each level has been set to 2200 mm, which corresponds to the 16% percentile of the distribution of 2-year accumulated amounts measured by 440 gauges. It is worth noting that the highest threshold (6600 mm in 2 years) is of the same order of magnitude of the maximum recorded by the 440 gauges. The pattern of the region with more than 4400 mm in two years (dark grey and black) is reasonable after the WMR adjustment; on the contrary it is too small and erroneously displaced after a simple bulk adjustment. This can be further observed in Fig. 3, in which the thresholds (between the 4 levels of gray) are set at approximately 16%, 50% and 84%

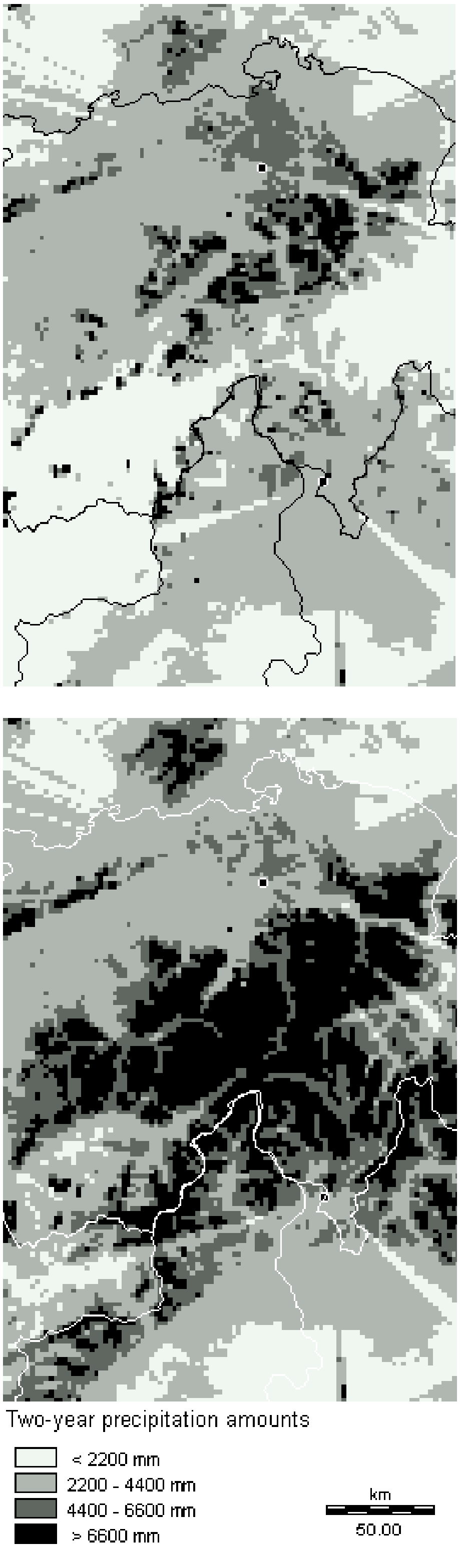

Fig. 2. Two-year precipitation amounts derived using the network of MeteoSwiss C-band radars and displayed using a linear intensity scale with saturation (four 1100 mm/year classes) (Top) Bulk-adjusted data. (Bottom) WMR-adjusted data.

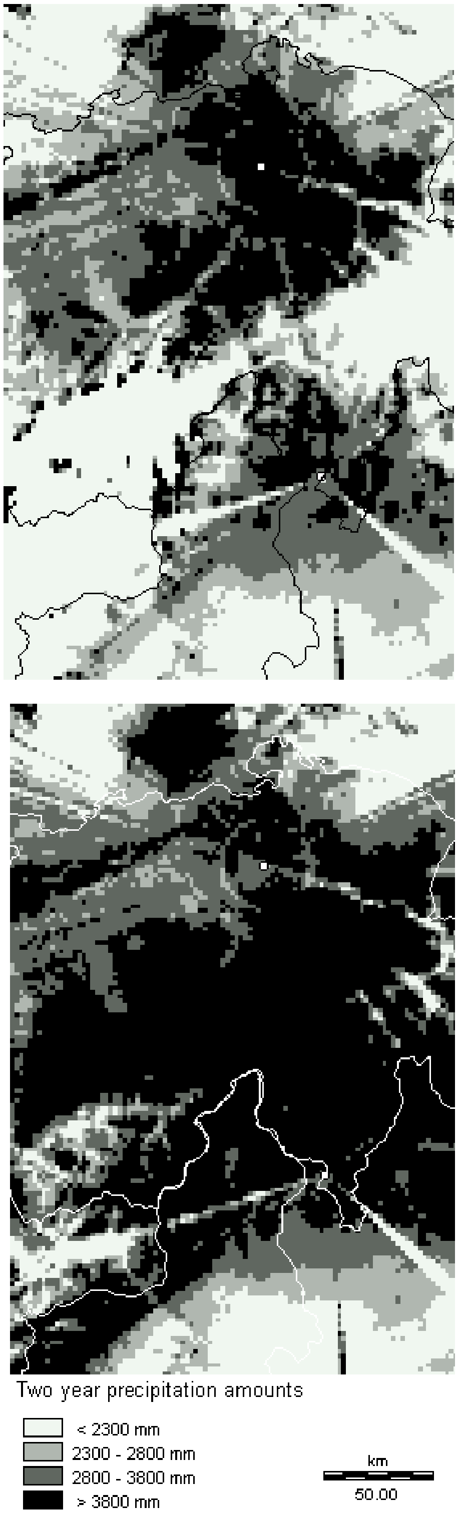

Fig. 3. Two-year precipitation amounts derived using the network of MeteoSwiss C-band radars and displayed using 4 classes, which are based on the 16%, 50%, and 84% percentiles (see Table 2) of the rain gauge values. (Top) Bulk-adjusted data. (Bottom) WMR-adjusted data.

Table 3. Verification results in terms of root mean square of the (Radar-Gauge) Areal Differences of rainfall amounts cumulated over two years.

	Raw	Bulk-adjusted	WMR-adjusted
All 442 R-G couples	1721 mm	1014 mm	792 mm
415 "QC" R-G couples	1701 mm	907 mm	675 mm

percentiles measured by the gauges. Precipitation amount distributions, as for many atmospheric variables, are distinctly asymmetrical, and skewed to the right. Very often the skewness occurs the more the nearest is the physical limit on the left to the range of data: with 2-year integration period it is obviously less pronounced than during shorter periods. As can easily be derived from the 1st line of Table 1, the bulk-adjustment factor (~2.1) gives 84% percentile (4398 mm) and spread (1756 mm) values that are probably too large.

On the contrary, spread and 84% percentile are more similar between WMR-adjusted and Gauge values (last two lines of Table 2).

The average values of the WMR coefficients (derived from a set of 442 regressions that are based on 441 couples) are:

$$\boldsymbol{F}_{dB} = -0.8 - 0.6 \cdot Log\,(\boldsymbol{D}) - 1.4 \cdot \boldsymbol{HV} + 1.8 \pm \cdot \boldsymbol{HG} \quad (2)$$

The variance explained by this multiple regression is ~38%. 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: on average, the Radar-to-Gauge ratio, F_{dB}, increases with increasing Height of the Ground. In past WMR analyses, a remarkable orographic influence on F_{dB} was not revealed: a_{HG} usually spanned both negative and positive values. Those analyses (variance explained ~60%) also referred to the Alps (Gabella 2004), but to a smaller set of gauges (of the order of 50), a smaller area (~12 000 km^2) and shorter integration periods (24 h).

The areal estimate of precipitation is of major interest for several applications. The agreement between radar and in situ measurements can however only be checked at "points" (with some reasonable information from the gauges). The variability of rainfall and the extreme differences in sampling modes are relevant when comparing values from radar and rain gauges: a radar "instantaneously" samples a volume high up in the sky every few minutes, while a rain gauge continuously records at a single point on the ground. Consequently, we decided not to compare each individual "point" measurement and the corresponding radar estimate; we instead opted for areal estimates over rectangular patches of 65×55 km^2. All gauges lie in 21 of these patches. We then derived an array of 21 Areal Differences. To summarize the results, we opted for the root mean square of these 21 elements (1st line of Table 3).

Table 4. Verification results in terms of (Radar-Gauge) Fractional Standard Areal Differences of rainfall amounts cumulated over two years.

	Raw	Bulk-adjusted	WMR-adjusted
442 R-G couples	0.61	0.36	0.28
415 “QC” R-G couples	0.59	0.31	0.23

Table 5. Verification results in terms of (Radar-Gauge) Fractional Standard Areal Differences of rainfall amounts cumulated over two years using two mutually exclusive subsets of (208 and 207) “QC” Radar-Gauge couples (when the 1st one is used for training the coefficients, the 2nd one is used for the verification and vice versa).

Subset used for the verification	Raw	Bulk-adjusted	WMR-adjusted
Second subset	0.58	0.30	0.22
First subset	0.59	0.31	0.23

The quantitative comparison with rain gauge amounts was then restricted to a subset of “Quality Checked” (QC) couples[2]. In this example the criterion used was simply the normalized Radar-to-Gauge ratio F_n; the normalization was performed with respect to the overall total of all the available time-cumulated Radar and Gauge amounts. The “acceptable” range of variability for F_n is chosen to be ±5 dB. In this case we get from Table 2 a value $F_n = 0.48$ (acceptable range is from −8.2 dB up to +1.8 dB) rejecting 27 couples. By applying again the WMR, we get:

$$\boldsymbol{F}_{dB} = -0.5 - 0.8 \cdot Log\,(\boldsymbol{D}) - 1.3 \cdot \boldsymbol{HV} + 1.4 \cdot \boldsymbol{HG} \quad (3)$$

In this case the variance explained by the regression increases to 41%. This new set of coefficients has been used to compute the *root mean square* of the Areal Differences, *rms*(**AD**), which is shown in the 2nd line of Table 3 and involves twenty $66\times50\,\text{km}^2$ patches.

(It is worth noting that 19 rejected stations are in the eastern part of Switzerland where the radars visibility is poor). To ease the comparison with the weather classes that will be used in the next Sections (and are obviously associated with smaller average values of precipitation), *rms*(**AD**) is normalized to the average precipitation to obtain a “Fractional Standard Areal Difference”, which is shown in Table 4.

If the training is based on two mutually exclusive subsets of (208 and 207) “QC” radar-gauge couples, the following WMR coefficients are obtained

$$\boldsymbol{F}_{dB} = -0.5 - 0.7 \cdot Log\,(\boldsymbol{D}) - 1.4 \cdot \boldsymbol{HV} + 1.5 \cdot \boldsymbol{HG} \quad (4)$$

$$\boldsymbol{F}_{dB} = -0.3 - 0.9 \cdot Log\,(\boldsymbol{D}) - 1.2 \cdot \boldsymbol{HV} + 1.3 \cdot \boldsymbol{HG} \quad (5)$$

while for the verification, the “Fractional Standard Areal Difference” values are shown in Table 5.

5 Weather dependent analysis and results

Since 1945 the Alpine Weather Statistics (AWS) has been available for the central European Alps. Its 34 parameters are defined on a daily basis by MeteoSwiss using a set of objective criteria. A description of the AWS can be found in Wanner et al. (1998). The AWS parameter nr. 33 denotes the daily weather classification into 40 classes, commonly referred to as the “Schüepp Wetterlageneinteilung”. This synthesizes five out of the 34 AWS parameters, namely geostrophic surface wind direction, wind speed at 500 hPa, wind direction at 500 hPa, geopotential height at 500 hPa, and baroclinicity. The Schüepp classification scheme consists of 40 different weather classes which describe the synoptic situation at 12 UTC on a daily basis with a geographical focus on the Alpine region (defined by a circular area with radius of ∼220 km and center in south-eastern Switzerland) and is also available since 1945. For this study, the 40 classes according to Schüepp have been grouped into 8 larger classes, roughly separating the different weather situations into:

- four advective classes (“South”, “North”, “West” and “East”), which are characterized by appreciable surface winds and southerly, northerly, westerly and easterly winds at 500 hPa;
- three convective classes (“Flat”, “Low” and “High”), which are characterized by weak surface winds and average, below and above normal geopotential height on 500 hPa;
- a “Mix” class.

In terms of precipitation amounts, the eight classes are obviously characterized by quite different values (see Table 6, 2nd column): “East” (advective) is the most driest one, “Flat” (convective) is the most rainy one. As far as the other two convective classes are concerned, it may be said that class “High” is characterized by fair weather with only light to moderate rain, whereas for “Low” more intense precipitation is typical. Also the normalized Radar-to-Gauge Factor, F_n, shows a certain variability namely 4.2 dB, (4th column): however, it turns out that the radar does not overestimates the average precipitation in any weather class. The number of couples for which the normalized Radar/Gauge ratio lies outside a 10 dB interval (i.e. the number of rejected couples) is between a few per cent and 20% (last column of Table 6).

Table 7 shows the results of the verification in terms of “Fractional Standard Areal Difference” using all the available 442 Radar-Gauge couples (actually for the “East” class

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[2] For the sake of simplicity, we have used a “hard” selection procedure; we nevertheless think it is worthwhile to seek for probabilistic, “fuzzy” QC (maybe using “continuous: weights rather than “0/1” discrete weights)

Table 6. Alpine Weather Statistics (Schüepp) with 8 weather classes for the two-year period from December 2000 to November 2002.

Type of weather class	Average cumulative precipitation	Number of days	Fn in dB	Number of "QC" Radar-Gauge couples
"Flat"	873 mm	253	−2.8 dB	425
"South"	465 mm	62	−3.6 dB	405
"North"	421 mm	104	−3.6 dB	369
"Mix"	420 mm	57	−4.2 dB	410
"West"	409 mm	71	−3.2 dB	390
"Low"	283 mm	41	−4.0 dB	400
"High"	122 mm	128	−0.0 dB	437
"East"	15 mm	14	−3.2 dB	351
Total	3008 mm	730		

Table 7. Verification results in terms of (Radar-Gauge) Fractional Standard Areal Differences. All 442 Radar-Gauge couples have been used.

	Raw	Bulk-adjusted	WMR-adjusted
"Flat"	0.55	0.32	0.25
"South"	0.76	0.52	0.35
"North"	0.69	0.40	0.33
"Mix"	0.74	0.45	0.33
"West"	0.64	0.43	0.37
"Low"	0.67	0.36	0.28
"High"	0.33	0.33	0.26
"East"	0.70	0.46	0.44

Table 8. Verification results in terms of (Radar-Gauge) Fractional Standard Areal Differences. Only "QC" Radar-Gauge couples have been used both in the training and in the verification.

	Raw	Bulk-adjusted	WMR-adjusted
"Flat"	0.54	0.28	0.20
"South"	0.70	0.40	0.28
"North"	0.66	0.31	0.26
"Mix"	0.73	0.40	0.26
"West"	0.59	0.35	0.29
"Low"	0.65	0.30	0.23
"High"	0.28	0.28	0.22
"East"	0.64	0.45	0.35

there are only 431 stations where both radar and gauge amounts are different from zero). We think Table 8 could be more significant and robust since it shows the results for the "QC" couples only. In all cases, the WMR-adjustment, which is variable in space, performs better than a uniform bulk-adjustment. However, a point of caution has to be raised for the last two classes, which are associated with small average rainfall amounts. It is significant that for these two classes (emphasized in italics in the Tables), the variance explained by the WMR never reaches 20%! Another noteworthy aspect of the training is that for the six weather classes that are characterized by the largest rainfall amounts, the coefficients a_D and a_{HV} are negative. On the contrary, a_{HG} is positive. The variance explained ranges from 32% ("Low") to 49% ("South").

Rainy days associated with high pressure conditions ("High") show Fractional Standard Areal Difference significantly smaller than all other classes. This fact will be certainly investigated in future.

6 Summary and conclusions

This paper presents a quantitative comparison over Switzerland (~41 000 km^2) between 442 gauge-measured and collocated radar-derived rainfall amounts accumulated from December 2000 to November 2002. Radar data come from the MeteoSwiss network of three C-band Doppler radars: the troposphere is scanned every 5 min (with 1°×80 m resolution) using 20 interleaved elevations; data processing includes 7-step clutter elimination, compensation for vertical profile of reflectivity and partial beam shielding. The root mean square of the Areal Differences, *rms*(**AD**), turns out to be ~1700 mm (average 2-year precipitation measured by the 442 gauges is 3008 mm). A uniform bulk-adjustment, that is a single adjustment coefficient which is simply the ratio between Gauge total and the collocated Radar total, reduces it to 900 mm. Using a non-linear Weighted Multiple Regression (WMR) to derive an adjustment factor, which is function of the Distance from the radar, the Height a weather target must reach to be Visible to the radar and the Height of the Ground, *rms*(**AD**) reduces to 675 mm. The WMR approximately explains 40% of the variance characterizing the Radar-to-Gauge ratio variability at all gauge sites. Hence, a first relevant conclusion is that the WMR is well worth the effort of deriving three additional coefficients to replicate beam broadening, visibility and orography (in addition to the overall bulk adjustment).

The 2-year rainfall amounts have been then stratified according to 8 weather situations of the Alpine Weather Statistics. Again the WMR always shows better performances than a uniform bulk-adjustment. If we look at the *rms*(**AD**), we could conclude that the WMR works well for all 8 weather situations. Actually, while for the first six rainiest classes (average rainfall), the variance explained by the WMR ranges from 32% to 49%, for the last two classes it does not even reach 20%. This confirms previous findings where the WMR proved to work better during intense and extreme events rather than during light rain: in days with "strong" weather signal, the WMR is able to correct several errors in one step ("calibration", beam-broadening, shielding and orographic enhancement).

Results on regional basis in dependence on the weather situation should still be checked and will be performed in future.

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