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Review scientific paper

Analysis of radar precipitation estimation in Central Croatia

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Abstract

Good monitoring of precipitation is of great importance in many fields of human activity that use meteorological information. Precipitation is highly variable in space and time and therefore it is advisable to use tools that provide good spatial and temporal resolution of the phenomenon. The meteorological radar from the Radar Center of Bilogora is used for this purpose. However, radar precipitation is not measured directly but is estimated in a way that reflected electromagnetic signal turns into precipitation using the Z-R relation. This paper analyses the period from 1. 12. 2015. to 31. 8. 2016., comparing the ground measurements of hourly accumulated precipitation from the main meteorological stations and radar associated pixels precipitation estimation. It was found that radar overestimates precipitation. It is possible to reduce such systematic radar estimation errors with a climatological bias adjustment.

Keywords

Precipitation, main meteorological station, meteorological radar, Z-R relation, bias adjustment.

1. Introduction

Precipitation is one of the most unpredictable parameters in meteorology. A good understanding and monitoring of precipitation is essential not only in scientific and professional circles, but also in other branches of human activity that use meteorological information (e.g. **Jelić, 2013**). Precipitation varies in time and space, hence it is necessary to use proper tools for good spatial and temporal resolution of this phenomenon, and therefore, there is a need for radar measurements. The main advantage of radar measurements is high spatial and temporal resolution. The working principle of radar is transmitting an electromagnetic wave in different directions in the atmosphere and receiving back weakened reflected waves as a signal.

1.1. Radar and radar equation

Radar is composed of transmitter of electromagnetic (EM) waves, antenna, receiver and display. The received signal, P_r, is calculated by using the radar equation:

$$P_r = \frac{\pi^3 p_t g^2 \theta \varphi c t K^2 I z}{1024 \ln(2) \lambda^2 r^2} \tag{1}$$

Where:

P_r – power of transmitted signal,
g – gain of antenna
θ, φ – horizontal and vertical angle beam width,
c – speed of light,
t – pulse duration,
K^2 – parameter associated with complex index of refraction of the observed material,
I – attenuation,
z – reflectivity factor,
r – distance from the radar,
λ – wavelength.

The reflectivity factor depends on the amount and size of droplets in a given volume and is determined by:

$$z = \sum N_i D_i^6 \tag{2}$$

Where:

N_i – amount of droplets,
D_i – droplet diameter.

Thus acquiring values of z ranging from $10^{-3}[mm^6 m^{-3}]$ to $10^7[mm^6 m^{-3}]$ which is why it is considered at a logarithmic scale. Logarithmic reflectivity Z is defined as:

$$Z = 10 \log_{10}\left(\frac{z}{1 mm^6 m^{-3}}\right) \tag{3}$$

Logarithmic reflectivity Z is expressed in dimensionless quantity [*dBZ*] which represents the logarithmic ratio between logarithmic power in decibels (*dB*) and reflectivity *z*. Such defined reflectivity takes values from -32 *dBZ* to 96 *dBZ* whereby precipitation consider values ranging from 0 to 55 *dBZ* for snow and rain, and

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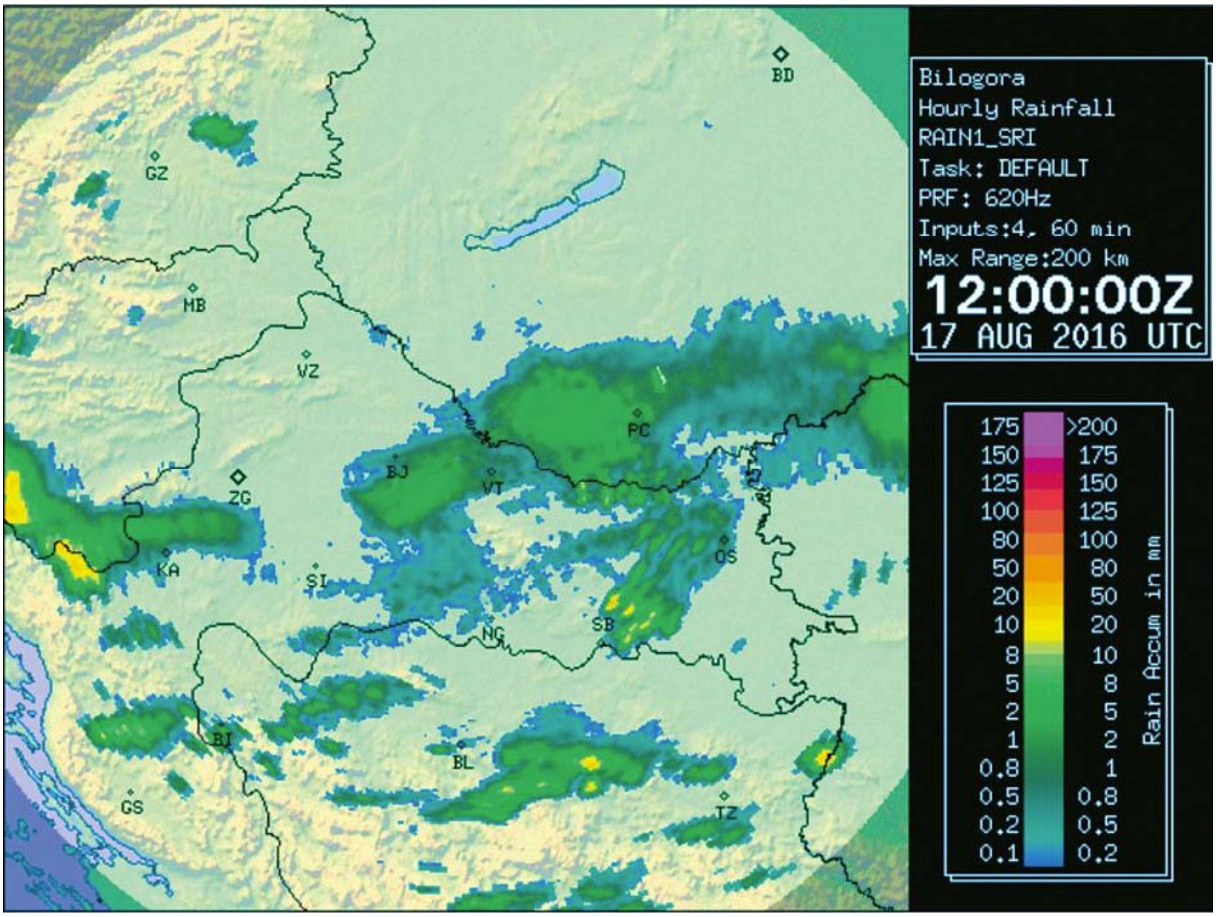

Figure 1: Radar precipitation estimation example of RC Bilogora; August 17th 2016. at 12:00

about 55 *dBZ* and higher for hail (**Frugis and Wasula, 2011**).

1.2. Z-R relation

Radar reflectivity depends on the diameter of the droplets to the power of six and the number of droplets of certain diameter. **Equation 2** is converted into an integral form and such an integral is calculated by all diameters in the reference volume, which leads to information about radar reflectivity in that volume. Precipitation intensity can be defined as:

$$R = \frac{\pi}{6}\int N(D) D^3 V_t(D)\, dD \qquad (4)$$

Where:

D – droplet diameter,
$N(D)$ – number of individual droplets,
$V_t(D)$ – thermal velocity of individual droplet.

Using **Equation 4**, Marshall-Palmer's exponential droplets distribution $N(D) = N_0 e^{-\lambda D}$ (**Marshall and Palmer, 1948**), and thermal droplets falling velocity $V_t(D) = 1400 D^{1/2}$ (**Spilhaus, 1948**), it is possible to derive an empirical Z-R relation that connects the reflectivity and precipitation intensity:

$$z = aR^b \qquad (5)$$

Where:

R [mm/h] – precipitation intensity,
a, b – empirical coefficients (**Wilson and Brandes, 1979**).

Values of these coefficients are found in the range $0 < a < 500$ and $1 < b < 2$ (**Shelton, 2009**). Each relationship between the radar reflectivity factor *Z* and rainfall rate *R* (Z-R relation) is associated with a type of precipitation, season and region. Radar does not measure precipitation directly, but estimates it based on measured reflectivity that comes from clouds. Radar samples observed volume in one *ms* and returns on the same volume in 5 to 15 *min* depending on the radar settings. A time lag is present between radar precipitation estimation and ground-level measurements due to droplets exceeding a certain way until falling to the ground. There are lot more factors affecting deviations of radar estimations from ground-level measurements. A Z-R relation is determined in several ways. The first is by comparing ground-level measurements and radar reflectivity (**Hunter, 1999; Rinehart, 2004**). The second way is to define a Z-R relation using cumulative distribution function (**Atlas et al., 1990; Mushore, 2012**).

There are various Z-R relations (**Equation 5**) depending on precipitation type, geography and other. If radar estimates match with ground-level measurements, it can be concluded that all points of the radar area provide a good precipitation estimation. Ground-level measurements are spatially still very coarse, which contributes to the overall uncertainty while denser measurements are usually not possible because of lack of finance (**Borga, 2002**). Hence, there is need for alternative methods of precipitation measurements. Long range sensing, by meteorological radar for example, in the last 50 years is having a more important role in natural phenomena observation and adds a lot of attention to their development (**Rinehart, 2004**).

1.3. Precipitation measurement and assessment of uncertainties

A rain gauge station also has a measurement error that is greater as surface wind is stronger. Furthermore, a meteorological station covers a very small area compared to the area that it represents, and during local convective processes it may happen that rainfall was not recorded. On the other hand, there are a number of factors that directly affect return signal i.e. reflectivity z and cause uncertainty. Some of them are: attenuation, atmospheric refraction, bright band, droplet distribution, reflection from non-meteorological targets (e.g. **Hunter, 1999; Rinehart, 2004; Lee and Zawadzki, 2005; Holleman, 2006**).

Attenuation results from the passage of electromagnetic waves through a medium. In icy clouds, attenuation is almost negligible, whereas in water clouds, it can reach up to *4.8 dB/100km* for $\lambda = 3.2$ *cm* (e.g. **Rinehart, 2004**). In large and strong convective systems, attenuation can be large enough to suppress the signal in that volume direction, thus losing information about the processes behind that system (**Jelić, 2013**). Atmospheric refraction is deviation of an electromagnetic wave from a straight line due to passage through the atmosphere because of changes in air density by height. In case of a negative density gradient, the curvature of the beam will be greater than the curvature of the Earth's surface, and thus, the beam can hit the ground. Bright band occurs in an area where ice crystals transform into water droplets. Water better reflects EM waves and in that layer, enhanced reflectivity occurs. The reflection of non-meteorological targets can be caused by dust, insects, airplanes, forests, buildings, mountains, etc. Static targets pose no problem as it is easy to recognize them on radar images.

1.4. Radar beam properties

Reflectivity depends upon the width of the radar beam and because it is 2°, its width is twice as large at double distance from the radar. Therefore, smaller processes at greater distances from the radar are misinterpreted. The coverage area radius of radar from the Radar Center (RC) Bilogora is 240 *km* (see **Figure 1**).

2. Methods

The main objective of this paper is the calibration of radar precipitation estimation. A wider area of Central Croatia covered by radar of the RC Bilogora has been observed for this purpose. A comparison of radar estimation and ground-level measurements was made. Hourly values of precipitation were taken from the above mentioned stations for the period of December 1st 2015. – August 31st 2016. Hourly radar estimations were created for the same period. For that purpose, the data collected in *HDF5* format was unpacked using *R-statistics* software to obtain maps of 480 x 480 resolution dots (which is equivalent to pixel dimension of about 1 x 1 km^2). For the purpose of this paper, the problem of the radar beam spreading is neglected and is assumed that pixel dimensions are equal in size at all distances from the RC Bilogora. As already mentioned, poorer resolution over longer distances is likely to be a major cause of uncertainity between radar estimation and ground-level measurements of precipitation (**Jelić, 2013**). Since ground-level measurements have hourly time step intervals, every 15-minute radar estimation sample is converted into an hourly value using Z-R relation. It was necessary

Table 1: Geographical characteristics of meteorological stations

Station	Geo. coordinates	Elevation (m)	Distance from radar (km)
Varaždin	46°16'57"N 16°21'51"E	167	78
Krapina	46°08'16"N 15°53'18"E	202	105
Puntijarka	45°54'27"N 15°58'06"E	991	95
Zagreb – Maksimir	45°49'19"N 16°02'01"E	123	91
Karlovac	45°29'37"N 15°33'54"E	110	134
Ogulin	45°15'46"N 15°13'20"E	328	168
Sisak	45°30'00"N 16°22'00"E	96	78
Križevci	46°01'43"N 16°33'17"E	157	53
Bjelovar	45°54'35"N 16°51'10"E	141	27
Bilogora	45°53'01"N 17°12'02"E	262	0
Daruvar	45°35'29"N 17°12'37"E	154	31
Gorice	45°13'25"N 17°16'42"E	135	74
Slavonski Brod	45°09'33"N 17°59'43"E	88	100
Osijek	45°30'09"N 18°33'41"E	89	114

to determine the corresponding radar pixel for each meteorological station. That is achieved using *Q-GIS* and *R-statistics* software, where a case with an influential area of one pixel (about 1 x 1 km^2) is observed. In order to process hourly precipitation time steps, it was required to use data from automatic meteorological stations. **Table 1** shows 14 selected stations that are located within a radar beam radius.

Table 2: The sum of ground-level precipitation measurements on meteorological stations and radar precipitation estimation at corresponding pixel for the period December 1st 2015. – August 31st 2016.

Station	Sum of radar precipitation estimation (mm)	Sum of ground-level precipitation measurements (mm)
Varaždin	899	598
Krapina	742	618
Puntijarka	1876	635
Zagreb-Maksimir	935	589
Karlovac	1171	741
Ogulin	980	1073
Sisak	769	645
Križevci	628	629
Bjelovar	571	552
Bilogora	708	416
Daruvar	967	723
Gorice	804	606
Slavonski Brod	491	500
Osijek	1059	495

3. Data processing

Each *HDF5* file was loaded into *R-statistics* software, and information about radar precipitation estimation was obtained. Pixels for each meteorological station were determined beforehand. Data was analysed from all of fourteen stations. The sum of the measured and estimated precipitation for the reference period is shown in **Table 2**. From the table below, it is possible to conclude that the radar generally overestimates the amount of precipitation if one looks at the sum over a longer period of time. For the period from December 1st 2015. to August 31st 2016., the maximal total measured amount of precipitation has been recorded at the Ogulin station (1073 mm) and the associated summary radar assessment matches relatively well with it. The maximal overall assessment by radar has a pixel corresponding to the Puntijarka station. This station together with the Osijek station has the greatest summary deviation of radar precipitation estimation from ground-level measurements.

Figure 2 shows the sum of precipitation estimation over Central Croatia for the period December 1st 2015 to August 31st 2016 obtained by using the *Inverse Distance Weighting* (IDW) interpolation method. IDW is applied

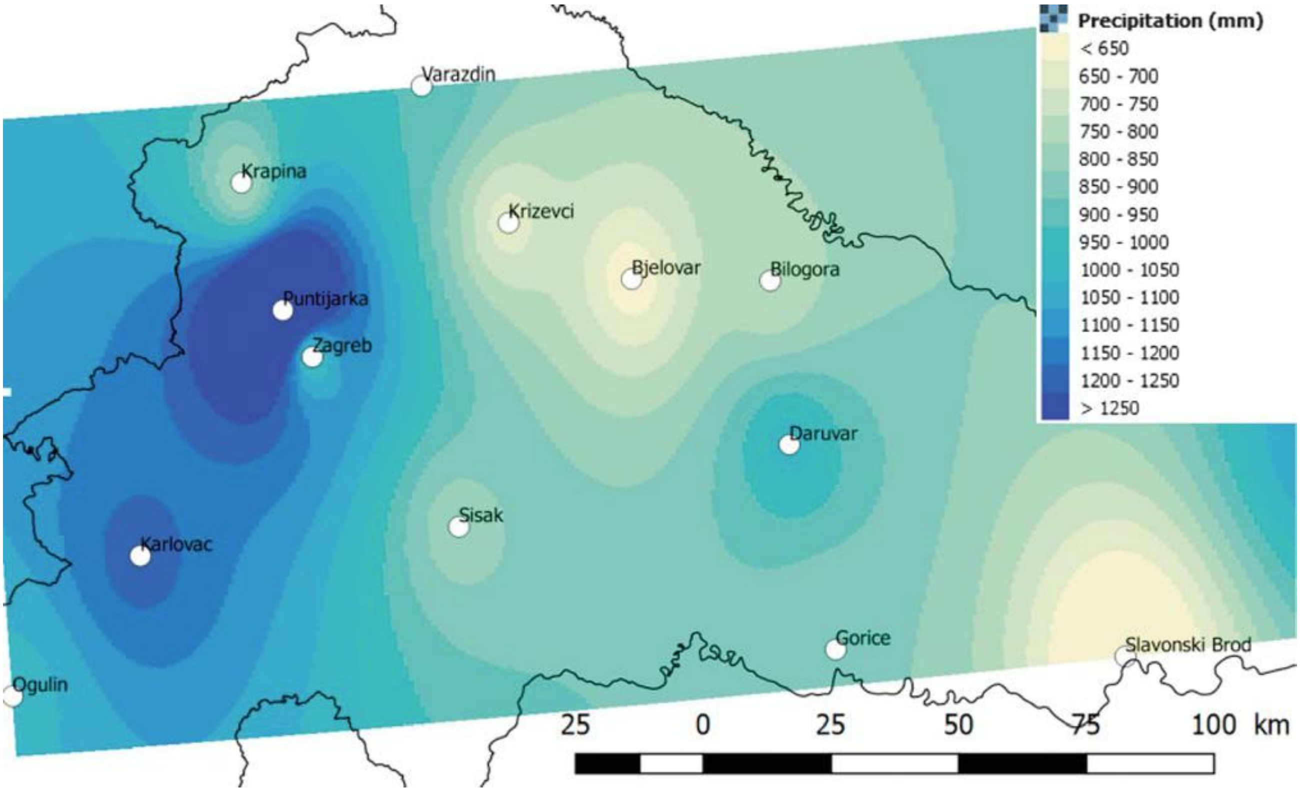

Figure 2: Inverse Distance Weighting (IDW) interpolation of precipitation estimation of Central Croatia for the period December 1st 2015. to August 31st 2016.

on the sum of radar precipitation estimation for each meteorological station. Inverse Distance Weighting is a type of deterministic method for interpolation with a known scattered set of points. IDW can be considered as a relatively simple interpolation in the case when a number and overall information about data is large enough that interpolation can replace the simplest zonal estimation (**Mesić Kiš and Malvić, 2014**), but still is not abundant enough that methods based on spatial analysis can be used (**Novak Zelenika and Malvić, 2014**). In fact, any mathematically advanced interpolation, especially Kriging-based technique and simulations, highly depends on an adequate amount of input that autocorrelation, and sometimes cross-correlation, can be modelled without any significant uncertainties. Using this method yields the spatial distribution of precipitation amount over the region of interest.

Interpolation was made in *Q-GIS* software. The Puntijarka station expectedly has the greatest amount of precipitation considering its elevation. The Karlovac station is far away from RC Bilogora, so that can be a reason for the unexpectedly high precipitation amount. Some stations, such as Zagreb, Varaždin, Križevci, Bjelovar, Bilogora, Sisak and Slavonski Brod have well described precipitation estimations. Generally speaking, the sum of radar precipitation estimation for the period December 1st 2015. to August 31st 2016. had good correlation with ground level measurements, with a few exceptions (e.g. the Puntijarka and Osijek stations).

3.1. Climatological bias adjustment of radar precipitation estimation

Remote sensing of precipitation, such as satellite and radar, have their own systematic estimation error. It is possible to reduce such systematic radar estimation error with climatological bias adjustment. It is based on the estimation of bias factor computed from rain gauge rainfall reports and corresponding radar rainfall grids:

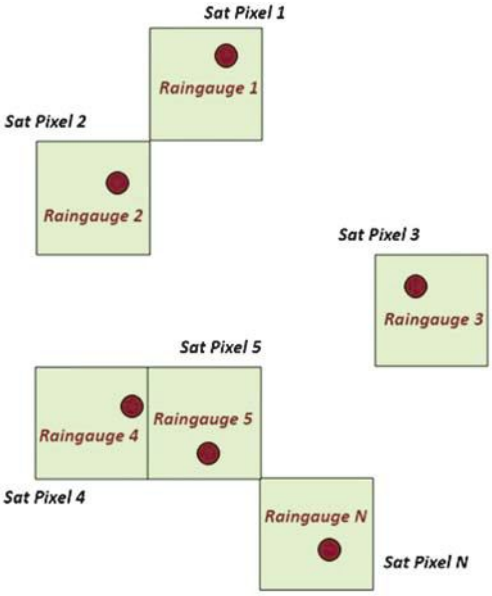

Figure 3: Example of rain gauge – radar pairs

$$B = \frac{\sum_{i=1}^{N_G} R_{G_i}}{\sum_{j=1}^{N_G} R_{S_j}} \tag{6}$$

Where:

R_{G_i} and R_{S_i} – ith rain gauge and jth radar pixel value corresponding to a rain gauge location,

N_G – number of rain gauge–radar pairs (see **Figure 3**).

In order to simplify the notation, it is assumed that there is only one rain gauge contained in each radar pixel. Regardless of the assumption, that condition is fulfilled in our case. If more are included, the arithmetic average of the values is used as the rain gauge value for that pixel.

3.2. Cumulative distribution function

Cumulative distribution function (CDF) of a random variable *X*, evaluated at *x*, is the probability that *X* will take a value less than or equal to *x*. It can be written as:

$$F_X(x) = P(X \le x) \tag{7}$$

Where the right-hand side represents the probability that the random variable *X* takes on a value less than or equal to *x*. The probability that *X* lies in the semi-closed interval *(a,b]*, where $a < b$, is therefore:

$$P(a < X \le b) = F_X(b) - F_X(a) \tag{8}$$

Every cumulative distribution function *F* is non-decreasing and right-continuous. Furthermore:

$$\lim_{x \to -\infty} F(x) = 0, \quad \lim_{x \to +\infty} F(x) = 1.(9) \tag{9}$$

The cumulative distribution function of the precipitation amount approach is necessary due to high uncertainty in single hourly radar estimation. Therefore, the aim is to improve the climatological, i.e. cumulative distribution of precipitation assessment over a period of 9 months. The goal is to reduce systematic error over a longer period of time and thus gain the climatological error correction. Therefore, the cumulative distribution function approach is a good way for determining bias factors. The cumulative distribution function is also an excellent indicator of whether radar overestimates or underestimates the real precipitation amounts.

4. Results

The order of precipitation events is not important for the purpose of climatological bias adjustment, therefore the data from stations mentioned above are arranged in a timeless series. All values lower than 0.5 mm/h are excluded since such phenomena are frequent and negligible. After the removal of redundant data, 2812 hourly

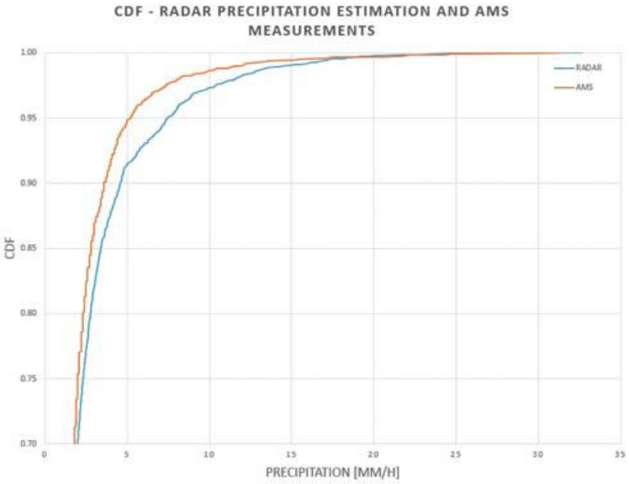

Figure 4: Cumulative distribution function (CDF) for radar precipitation estimation and ground-level measurements (AMS)

values of radar estimation and ground-level measurements remain. **Figure 4** shows the cumulative distribution function (CDF) of ground-level measurements by main automatic meteorological stations (AMS) and radar estimations. It is represented in the section where CDF is greater than 0.7, because the most data of interest is within it.

In almost 70 % of all hourly precipitation events, 2 mm/h or less was recorded, together by radar and meteorological stations. **Figure 4** also confirms the previous conclusion that because of its settings, radar overestimates precipitation amounts comparable to the ground-level measurements. Possible causes for that are: inadequate selected radar pixel, attenuation and short time series of precipitation. Climatological bias adjustment is performed in a way that sorted arrays of hourly precipitation amounts, both AMS and radar, are divided into ten equal parts and for each of the ten quantiles, the bias factor is determined.

Figure 5 shows bias factors by quantiles. Radar overestimates precipitation amounts throughout the range, mostly to its minimal and maximal values. **Figure 6** shows the CDF for ground-level measurements, radar estimates and radar bias correction. From there it is evident that the corrected radar estimate has better correlation with ground-level measurements.

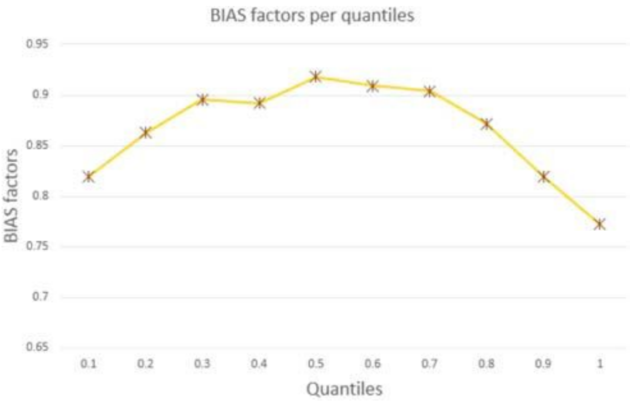

Figure 5: Bias adjustment factors of radar precipitation estimation by CDF quantiles

Pearson's correlation coefficients between hourly and daily values of radar estimations and ground-level measurements are determined. Also, Pearson's correlation coefficients between hourly values of radar estimations and ground-level measurements are determined without "no-precipitation" hours. "No-precipitation" hours are hours in which neither radar nor station did not record precipitation (see **Table 3**). The correlation coefficients of entire time intervals for each station are expectedly higher than those without "no-precipitation" hours. The reason for this is common case when there is no precipitation, i.e. when it hasn't been recorded neither by radar nor station. Daily correlation coefficients are higher than hourly, on average. Considering that in daily data samples, there is less loss of information than in hourly data samples, which is expected. One of the reasons is that precipitation recorded by radar needs some time to fall to the ground where it is then recorded by a rain gauge. Puntijarka (R_{day} = 0.421) and Ogulin (R_{day} = 0.696) stations expectedly have the lowest correlation coefficient between radar estimations and ground-level measurements, Puntijarka because of its high altitude and Ogulin due to a combination of higher altitude and distance from the radar. Although the Slavonski Brod station (R_{day} = 0.563) is at a satisfactory distance from the radar and at a low altitude, its correlation coefficient is quite small. One of the reasons is a small number of precipitation hours, but in order to make a more detailed analysis, further research is necessary.

The relationship between hourly radar precipitation estimation and ground-level measurements is shown in **Figure 7**, while the relationship between daily radar pre-

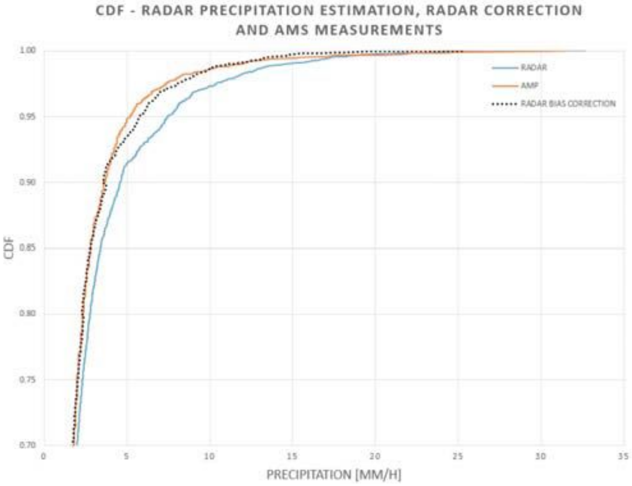

Figure 6: Cumulative distribution function (CDF) for radar precipitation estimation, bias correction of radar precipitation estimation and ground-level measurements (AMS)

Table 3: The correlation coefficient between radar precipitation estimation and ground-level measurements for hourly, daily and daily without "no-precipitation" days, and number of precipitation hours.

Station	R_{day}	R_h	R_h without no-precip. hours	Number of precip. hours
Varaždin	0.74454	0.77394	0.76381	1503
Krapina	0.76797	0.72538	0.69199	816
Puntijarka	0.42063	0.35782	0.26610	935
Zagreb-Maksimir	0.74164	0.77227	0.75710	1150
Karlovac	0.82297	0.72621	0.67069	785
Ogulin	0.69592	0.57103	0.46232	864
Sisak	0.72793	0.60109	0.57392	1011
Križevci	0.70677	0.67729	0.66631	2074
Bjelovar	0.85079	0.73314	0.72909	3554
Bilogora	0.70909	0.51751	0.48942	1917
Daruvar	0.72288	0.55784	0.54440	2818
Gorice	0.81151	0.60289	0.57016	1226
Slavonski Brod	0.56318	0.36719	0.25626	696
Osijek	0.71716	0.61281	0.58590	1094
Stations average	**0.76503**	**0.71322**	**0.70663**	**4584**

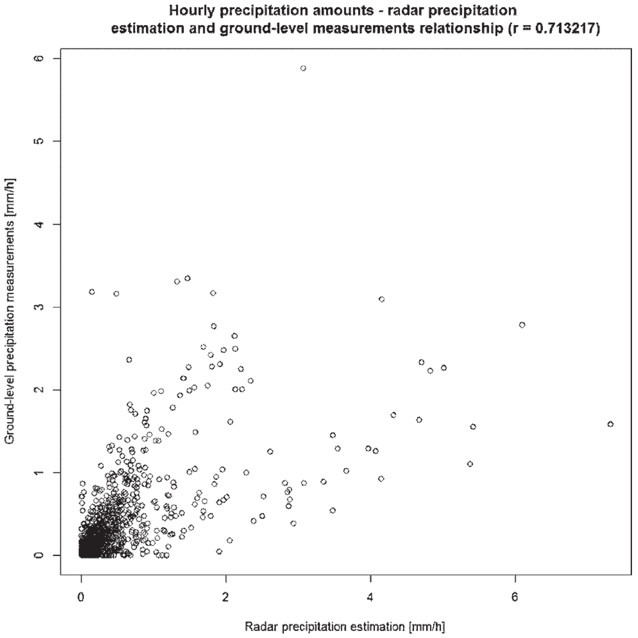

Figure 7: The relationship between hourly values of radar precipitation estimation and ground-level measurements

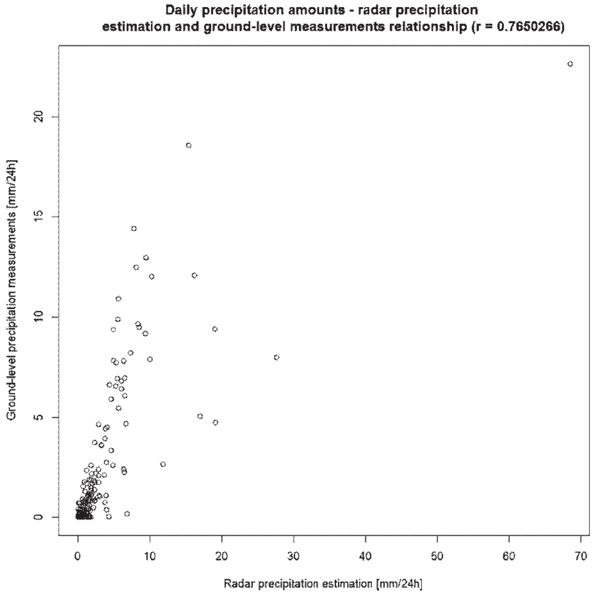

Figure 8: The relationship between daily values of radar precipitation estimation and ground-level measurements

cipitation estimation and ground-level measurements is shown in **Figure 8**.

5. Conclusion

The aim of this study was to evaluate the accuracy of meteorological radar of the RC Bilogora, determine the CDF and climatological bias of radar precipitation estimation due to the ground-level measurements and to calibrate it. Precipitation data was used for the period from December 1st 2015. to August 31st 2016. The ground-level measurements were obtained from fourteen main automatic meteorological stations that are also used for radar estimation calibration. The first part of the research showed that Bilogora meteorological radar overestimates ground-level measurements of precipitation. The most likely reasons for that are: an inadequate selection of radar pixel for precipitation estimation, signal attenuation and short time series. The second part of the research determined CDF of radar precipitation estimation and ground-level measurements, and the correlation coefficients between radar precipitation estimation and ground-level measurements. Bias correction factors were determined, also. Thus, the climatological radar precipitation estimation correction for the fourteen automatic meteorological stations in the selected period was created. In order to achieve progress in this field of research, future focus should be on the study of a longer time series, separated case studies of precipitation in rainfall form and snow form, and the selection of only those meteorological stations that do not have big radar precipitation estimation errors.

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SAŽETAK

Analiza radarske procjene oborina u Središnjoj Hrvatskoj

Dobro praćenje oborine od velike je važnosti u mnogim granama ljudskoga djelovanja koje se koriste meteorološkim informacijama. Oborina je varijabilna u vremenu i prostoru te je zato poželjno primjenjivati alate koji osiguravaju dobru prostornu i vremensku razlučivost te pojave. U tu se svrhu koristi meteorološki radar radarskoga centra Bilogora. No, radarom se oborina ne mjeri izravno, već se procjenjuje tako da se reflektirani elektromagnetski signal pomoću Z-R relacije pretvara u oborinu. U ovome radu analizirano je razdoblje od 1. prosinca 2015. do 31. kolovoza 2016. usporedbom zemaljskih mjerenja satne akumulirane oborine s glavnih meteoroloških postaja i radarske procjene oborine pripadajućih piksela. Utvrdilo se da radar precjenjuje oborinu. Takvu sustavnu pogrešku radarske procjene moguće je umanjiti klimatološkim prilagođavanjem pristranosti. Također, nacrtana je karta sumarne procjene oborine radarom za razdoblje od 1. prosinca 2015. do 31. kolovoza 2016. za središnju Hrvatsku interpolacijskom metodom inverzne udaljenosti.

Ključne riječi
oborina, glavna meteorološka postaja, meteorološki radar, Z-R relacija, klimatološko prilagođavanje pristranosti