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Quality index scheme for quantitative uncertainty characterization of radar-based precipitation

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ABSTRACT: A quality index scheme is proposed which is designed to evaluate the quality of different radar-derived rainfall products including processed radar data and precipitation accumulations. The idea of the quality index scheme is based on selection of quality factors, determination of their quality indices and computation of one final quality index. The factors were selected depending on the particular kind of precipitation field. In the proposed scheme the quality index for each quality factor is determined using regression relationships between quality factors and data errors calculated from rain gauge – radar observation differences. Finally, all the individual quality indices are summarized to a final quality index applying appropriate weights. The quality index is computed for each pixel of radar-derived precipitation field independently. The quality information field obtained in this way is attached to the radar-based precipitation product and can be used to generate the precipitation field as percentiles of probability density functions. Copyright © 2010 Royal Meteorological Society

KEY WORDS weather radar; uncertainty; quality; precipitation

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1. Introduction

1.1. Motivation

Nowadays, quality related issues are increasingly becoming part of main research fields. This trend affects weather radar data as well. Radar-derived precipitation data are burdened with a number of errors from different sources (meteorological and technical). Due to the complexity of radar measurement and processing it is practically impossible to eliminate these errors completely or at least to evaluate each error separately (Villarini and Krajewski, 2010). However, it seems that precise information about the data reliability is important for the end user. One of the ways to do this is to use a so-called quality index (*QI*), which can give quantitative information about quality/uncertainty of precipitation radar-based data. The starting point for the quality index computation is selection of quality factors related to quantities affecting the data uncertainty.

The estimation of radar data quality even as global quantity for single radar provides very useful and important information (e.g. Peura *et al.*, 2006). However, for some applications, such as flash flood prediction, more detailed quality information is expected by hydrologists (Sharif *et al.*, 2004; Vivoni *et al.*, 2007; Collier, 2009). A quality index approach for each radar pixel seems to be an appropriate way of quality characterization (Michelson *et al.*, 2005; Friedrich *et al.*, 2006; Szturc *et al.*, 2006, 2008b). As a consequence, a map of the quality index can be attached to the radar-based product.

1.2. Sources of uncertainty in surface precipitation estimated from weather radar data

There are numerous sources of errors that affect radar measurements of surface precipitation, which have been comprehensively discussed by many authors (e.g. Collier, 1996; Meischner, 2004; Šálek *et al.*, 2004; Michelson *et al.*, 2005). In this section the most important error sources are listed and briefly described.

Hardware sources of errors are related to stability of electronics, antenna accuracy and signal processing accuracy (Gekat *et al.*, 2004). Other non-meteorological errors are results of electromagnetic interference with the Sun and other microwave emitters, attenuation due to a wet or snow (ice) covered radome, ground clutter (Germann and Joss, 2004), anomalous propagation of radar beam due to specific atmosphere temperature or moisture gradient (Bebbington *et al.*, 2007), shielding due to topography (Bech *et al.*, 2007) or by nearby objects such as trees and buildings, and other non-precipitation echoes from birds and insects.

The next group of errors is associated with scan strategy, radar beam geometry and interpolation between sampling points, as well as the broadening of the beam width with increasing distance from the radar. Moreover, the

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beam may be not fully filled when the size of precipitation echoes is relatively small, or the precipitation is at low altitude in relation to the antenna elevation (overshooting).

Apart from the non-precipitation errors mentioned above, meteorologically related factors influence precipitation estimation from weather radar measurements. The most significant ones are described next.

Attenuation by hydrometeors, which depends on precipitation phase (rain, snow, melting snow, graupel or hail), intensity and radar wavelength, particularly C and X-band. Attenuation in hail may cause strong underestimation of precipitation.

The $Z-R$ relation expresses the dependence of precipitation intensity R on rainfall reflectivity Z. This empirical formula is influenced by drop size distribution, which varies for different precipitation phases, intensities and types of precipitation (convective or non-convective) (Šálek *et al.*, 2004).

The melting layer is located at the altitude where ice melts to rain. Since water is much more conductive than ice, a thin layer of water covering melting snowflakes causes strong overestimation in radar reflectivity. This effect is known as the bright band (Battan, 1973; Goltz *et al.*, 2006). In central Europe the melting layer effects are present in weather radar observations for almost the whole year.

The non-uniform vertical profile of precipitation leads to problems with the estimation of surface precipitation from radar measurement (e.g. Franco *et al.*, 2002; Germann and Joss, 2004; Einfalt and Michaelides, 2008). Moreover, these vertical profiles may strongly vary in space and time (Zawadzki, 2006).

Dual-polarization radars have the potential to provide additional information to overcome many of the uncertainties, in contrast to situations when only the conventional reflectivity Z and Doppler information are available (Illingworth, 2004).

In conclusion, the radar precipitation data are burdened with numerous errors that are difficult or impossible to be estimated quantitatively in many cases due to the complexity of the error structure in radar measurements. The approach proposed in the paper is not to use information about all known radar measurement errors, but to use more indirect quality information that is included in the processed data.

1.3. Quality factors in data quality characterization

The quality evaluation can be made on three levels corresponding to the stage in radar data processing (Holleman *et al.*, 2006):

1. the hardware level (where signal power is the output);
2. polar 3D volume (containing radar reflectivity), and,
3. final 2D product (surface precipitation rate).

In the present paper, the radar products reflecting surface precipitation rate are considered, as these data are most often employed, especially by the hydrological community. Such products can be constant altitude plan position indicator (CAPPI) or surface rainfall intensity (SRI), these being standard products in most weather radar systems. The products are assigned to specific measurement heights above sea level (CAPPI) or at nominal ground level (SRI).

The simplest metric of quality can be a mark (called a flag) indicating that data are either correct or incorrect. The flag values can equal zero or one (Michelson *et al.*, 2005).

The quality index (QI) is a measure of data quality and is a more detailed characteristic than a flag, providing quantitative assessment, for instance using numbers in a range from zero (for bad data) to some value for excellent data (e.g. 1, 100, or 255). The German DWD QI scheme is based not on numerical estimation but on encoded error types, e.g. attenuation, bright band, spikes and clutter (Helmert and Hassler, 2006; Helmert *et al.*, 2009).

The quality index concept is operationally applied to surface precipitation data in some national meteorological services. The schemes of the quality index calculation employ one or more quality factors. Distance to the nearest radar is one of the important factors related to radar beam broadening, due to the Earth's curvature effects, and is operationally used in ARPA-SIM (Italy), the Met Office (the UK) and IMGW (Poland), amongst others. The Spanish INM scheme (Gutiérrez and Aguado, 2006) uses a factor that is a map of percentage precipitation occurrences (precipitation is defined as reflectivity not less than 12 dBZ) during a few months reference period. In the Swedish SMHI (Michelson, 2006) a coefficient of adjustment with rain gauges is calculated as a quality factor, because rain gauge data after correction are considered to be precise at the gauge locations. In the UK Met Office (Harrison, 2007) and Finnish FMI (Peura *et al.*, 2006) spurious echoes are recognized and the related quality index is generated. MeteoSwiss employ beam blocking as a quality factor due to mountainous orography (Harrison, 2007). In the scheme developed in Météo France for their weather radar network in the frame of the PANTHERE project (Parent du Châtelet *et al.*, 2006; Tabary *et al.*, 2007) the height of the lowest beam is found to be a crucial factor, especially in mountainous areas, because of beam blocking and shielding. The Italian ARPA-SIM scheme (Fornasiero *et al.*, 2008) is designed for polar volume data from radars of the Emilia-Romagna region.

Moreover, for research needs, specific schemes are implemented. For instance, in the German DLR scheme (Friedrich *et al.*, 2006) distance to the radar site, beam blocking, existence of the melting layer and attenuation are taken into account. A similar scheme is used in hydro and meteo GmbH, Germany (Fennig *et al.*, 2009). In the French Novimet (Le Bouar *et al.*, 2008) the time sampling error, height of the lowest beam and 'intrinsic' error (depending on precipitation phase and polarimetric/non-polarimetric measurements) are important quality factors.

2. Definition of the *QI* scheme

2.1. Overview of a quality index

The overall scheme of the *QI* can be depicted typically as in Figure 1. In this scheme the following quantities must be determined.

1. Quality factors (X_i) – quantities that have impact on weather radar-based data quality. Their set should include the most important factors that can be measured or assessed. The factors can be, e.g. distance to radar, height of the lowest beam, attenuation in hydrometeors, ground clutter and related blocking and anomalous propagation echoes. Let the total number of the factors equal n.
2. Quality functions (w_i) for the quality factors X_i – formulae for transformation of each individual quality factor X_i into relevant quality index QI_i. The formulae can be linear or sigmoidal. The best solution is to determine the relationship according to physical properties of the given factor or by empirical analysis using any independent data source as a benchmark, e.g. the rain gauge network.
3. Quality indices (QI_i) – quantities that express the quality of data in terms of specific quality factors.
4. Weights (W_i) (in the case of additive formula Equation (5)) – weights of the QI_is. The optimal way of the weight determination seems to be an analysis of experimental relationships between proper quality factors and radar data errors calculated basing on comparison to rain gauge data.
5. Final quality index (QI) – the quantity that expresses the quality of data in total. In practice two solutions are considered to define this quantity: weighed average (Equation (5)) or multiplication of quality factors (Equation (6)).

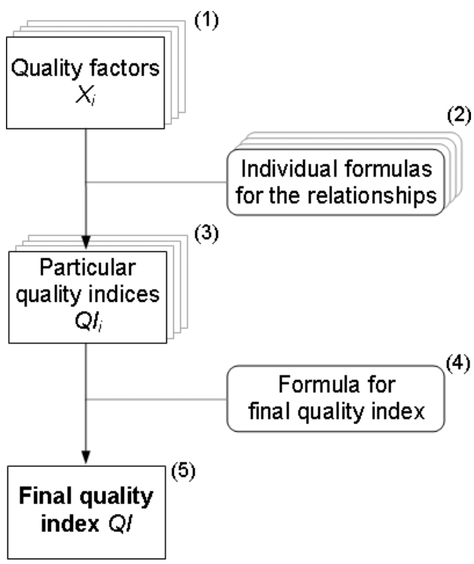

Figure 1. Overall scheme for quality index calculation.

2.2. *QI* scheme procedure

The proposed scheme is slightly modified in comparison with previously presented by Szturc *et al.* (2008b). A list of selected quality factors has been extended and nonlinear relationships between the factors and relevant quality indices are employed instead of linear ones. However, the main idea introduced in that paper is preserved here. The overall scheme is shown in Figure 1, and the detailed algorithms are outlined below. The proposed procedure is based on the following sequence of steps:

1. selection of n quality factors X_i (where $i = 1, \ldots, n$);
2. choice of an error characteristic, D, for radar-based data;
3. determination of QI_i (X_i) relationships' form based on a general equation:

$$QI_i = \begin{cases} 0 & \text{bad data} \\ 1 & \text{good data} \\ w_i(X_i) \in (0, 1) & \text{other cases} \end{cases} \quad (1)$$

where w_i is the quality function for i-quality factor;

4. for each quality factor X_i determination of threshold values of 'bad' and 'good' data ($QI_i = 0$ and 1 respectively) and critical values (their exceeding for any X_i results in final $QI = 0$);
5. calculation of quality indices QI_i for each quality factor X_i;
6. calculation of correlation coefficients $r_i = \text{corr}$ (X_i, D) on historical data set;
7. approximation of weights W_i for all quality factors X_i proportionally to the correlation coefficients r_i, and,
8. calculation of a final quality index QI from all QI_i values:

$$QI = QI(QI_1, QI_2, \ldots, QI_n) \quad (2)$$

The proposed quality index *QI* scheme is designed to evaluate the quality for each data pixel of different kinds of 2D surface radar precipitation data, i.e. radar data processed using data from other sources (e.g. rain gauge, NWP) to obtain surface precipitation estimates (*QPE*).

2.3. Set of quality factors X_i

For the precipitation rate a set of quality factors has been selected and divided into specific categories. The first is connected to measurement geometry and comprises distance to the nearest radar site and minimal height of radar visibility. The next group of factors is associated with the structure of the precipitation field, such as spatial and temporal variability. Another factor is a degree of the data corrections that reflect to what extent the radar-derived data were improved. For precipitation accumulation only two quality factors are applied: the number of rain-rate maps (products) that compose 1 h accumulation and the averaged quality index of rain rate products. All the quality factors employed in the paper are listed in Table I.

Table I. Set of quality factors used in quality index scheme.

Kind of precipitation data R	Quality factor X_i
Precipitation rate: precipitation estimate *QPE* (radar-based data after NIMROD processing)	*COR* – level of corrections (Equation (1)) *DR* – distance to the nearest radar site *MH* – height of the lowest radar beam (Figure 1) *SV* – spatial variability (Equation (2)) *TV* – temporal variability (Equation (2))
Precipitation accumulation from estimate *QPE*	*QIS* – averaged *QI* from precipitation rate products *NP* – number of rate products

2.4. Definitions of the selected quality factors

The quality factors listed in Table I as selected for the presented scheme are defined and discussed hereafter.

2.4.1. *Level of corrections*

Level of corrections (*COR*) is defined as the absolute value of difference between estimated radar-based data (*QPE*) and raw radar data (*QPM*):

$$COR = |QPE - QPM| \tag{3}$$

where *QPM* is the raw radar measurements after basic processing by the radar software, e.g. clutter removal, depending on the specific software.

The level of corrections provides summarized information about different measurement errors that are difficult to quantify separately: anomalous radar beam propagation (so called anaprop echoes), other spurious echoes (from interfering emitters and the Sun) and related to vertical profile of reflectivity (e.g. bright band effect), among others.

2.4.2. *Distance to the nearest radar site*

Distance to the nearest radar site (*DR*) is one of the most important factors for quality of surface precipitation measurements. The factor *DR* is calculated as horizontal distance from the given pixel to the radar site. This factor is not changeable with time, but may vary in the case of a radar network when some radars are not running at the current time.

Two main effects are connected with the factor: (i) the radar beam expands both in horizontal and vertical directions, and resulting inhomogeneous sample resolution leads to an increase of errors due to measurement averaging; moreover the beam cannot be homogeneously filled by meteorological targets, and (ii) the height of the lowest radar beam increases with the distance to radar due to the Earth's curvature (overshooting more likely to happen, effect of variability in vertical profile of reflectivity).

2.4.3. *Height of the lowest radar beam*

The height of the lowest radar beam (*MH*) is calculated from a digital elevation map (DEM) and the radar coordinates. It strongly depends on terrain complexity and related radar beam blocking. The definition of *MH*, as a minimum height for which radar measurement over a given pixel is feasible, is graphically illustrated in Figure 2.

The algorithm of the *MH* factor calculation is the following. At first, in subsequent steps the whole path from the nearest radar to the given pixel is investigated pixel by pixel. The height of the lowest radar scan due to blocking by every individual pixel on the path is estimated based upon the altitude of the pixel from a DEM map, distance from radar and increase of beam altitude due to Earth's curvature. Finally, the *MH* factor for a given pixel is assigned to a maximum value from the calculated heights of the lowest beam for all pixels on the path to the radar.

This factor has been found to be very important by many authors, e.g. Gabella and Amitai (2000), who propose the use of it as a quality factor in techniques of radar data adjustment with rain gauge measurements. In flat terrain the height *MH* depends only on the distance to nearest radar site *DR*. In mountainous terrain information included in the *MH* plays a key role on surface precipitation estimation due to such effects as radar beam blocking and shielding that are not considered in the factor *DR*. On the other hand, the *MH* is not sufficient because other factors included in *DR*, such as broadening of the radar beam, are not taken into consideration. Therefore, in more complex terrain both variables *DR* and *MH* become the significant quality factors, as correlation between them practically does not exist.

2.4.4. *Spatial and temporal variability*

Small scale variability of the precipitation field is directly connected to uncertainty, as high variability results in higher uncertainty, such as for small-scale convective phenomena. High precipitation intensity areas are

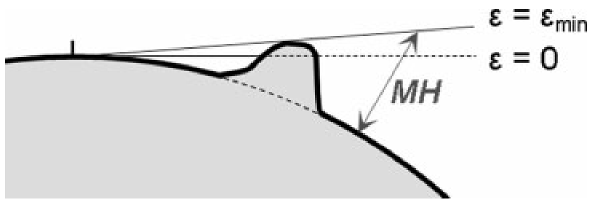

Figure 2. Definition of the height of the lowest radar beam (*MH*), where ε is the beam elevation.

more variable spatially and temporally. Moreover non-precipitation echoes, such as ground clutter, are often characterized by variability that differs from that for precipitation echoes.

Spatial (SV) and temporal (TV) variabilities are defined as a standard deviation σ in a certain spatial grid (for SV) or time window (for TV):

$$SV; TV = \sigma(R) = \sqrt{\frac{\sum_{i=1}^{N}\left(R_i - \frac{1}{N}\sum_{i=1}^{N} R_i\right)^2}{N-1}} \quad (4)$$

where N is the number of pixels in the spatial grid or the number of radar products in the time window. In the present work the number N equals 25 (5 × 5 pixels) for SV using 1 km data, and 4 for TV within a 30 min time window.

2.4.5. *Number of precipitation rate products*

The accumulated precipitation field is composed from a certain number of discrete radar measurements. The time resolution equals 10 min in POLRAD and NIMROD data (see Section 3.1). The 10 min periods between two subsequent radar images are long, especially if spatial resolution of the data is high. If clustering of rain pixels is observed, especially in the cases of convective cells and strong advection (Hannesen and Gysi, 2002; Jurczyk *et al*., 2008), more sophisticated algorithms are employed to overcome this effect, taking into account spatial and temporal interpolation of the precipitation fields.

The number of precipitation rate products (NP) is the number of the products included into precipitation accumulation. Lack of one or more products during the accumulation period results in a significant decrease of quality. The maximum value of NP equals seven in the case of 1 h accumulations and 10 min frequency of radar measurements (including the two outermost products).

2.4.6. *Averaged quality index from precipitation rate products*

For precipitation accumulation an averaged quality of all precipitation rate products available in a given time period (QIS) is the second quality factor. The factor is computed as a mean from NP values of QI for rates (e.g. maximally seven for 10 min resolution and 1 h period of accumulation) that are aggregated into the accumulation.

2.5. From quality factors X_i to final quality index QI

2.5.1. *Particular quality functions w_i and quality indices QI_i*

The most crucial point of the QI scheme is its parameterization. In the first step forms of the particular relationships between X_i and QI_i, that are expressed by quality functions w_i in Equation (1), must be found. A linear formula is an *a priori* assumption in the literature (Michelson *et al*., 2005; Friedrich *et al*., 2006; Le Bouar *et al*., 2008; Szturc *et al*., 2008a). Moreover, other formulae such as tricube (Clark and Slater, 2006) and sigmoid (commonly used in artificial neural networks) may be employed.

In the literature, formulae for such quality factors such as DR and MH can be found. The form of the relationship for DR has been established based on climatological data. The simplest approach is to assume that the accuracy of the measurements decreases linearly with distance to the radar (Friedrich *et al*., 2006), however most often non-linear formulae are taken, such as exponential (Fornasiero *et al*., 2005) or second order polynomials (Michelson *et al*., 2000). For MH, Gabella and Amitai (2000) assumed its linear impact on radar precipitation quality.

Empirical formulae have been applied here. Thus, different formulae determined on historical data from regression between each X_i factor and data error D (see Section 2.6) are employed to express the relationships $QI_i = w_i(X_i)$. Due to the empirical approach of the procedure the formulae are related to physical properties of each factor.

Moreover a critical value $X_{i\text{crit}}$ (after its exceeding the final QI is assigned to zero) and two threshold values X_{i0} and X_{i1} for which QI_i equals zero and one respectively should be determined. The parameterization of the presented scheme is described in detail in Section 3.

2.5.2. *Final quality index QI*

After determination of all QI_i (X_i) relationships, the final quality index $QI = QI(QI_1, QI_2, \ldots, QI_n)$, where QI_i is the quality index for specific quality factor X_i, is calculated. The QI is computed by aggregation of all the QI_i using an appropriate set of weights:

$$QI = \sum_{i=1}^{n} (W_i \cdot QI_i) \quad (5)$$

The weights are empirically estimated as described in Section 3. The final quality index QI is assigned to each pixel (grid) in the precipitation field.

For the precipitation accumulation products another formula to calculate the final QI is employed, in which particular quality indices QI_i are multiplied (e.g. Fornasiero *et al*., 2005) instead of summed:

$$QI = \prod_{i=1}^{n} QI_i \quad (6)$$

2.6. Characterization of radar data error

The common approach is to use rain gauge data as a benchmark for evaluation of radar data quality, as it is practically the only independent and reliable source of precipitation data. The rain gauge and radar data are quite different in terms of their spatial and temporal structure and errors. Rain gauge measurements are made at a specific location with limited and well known errors,

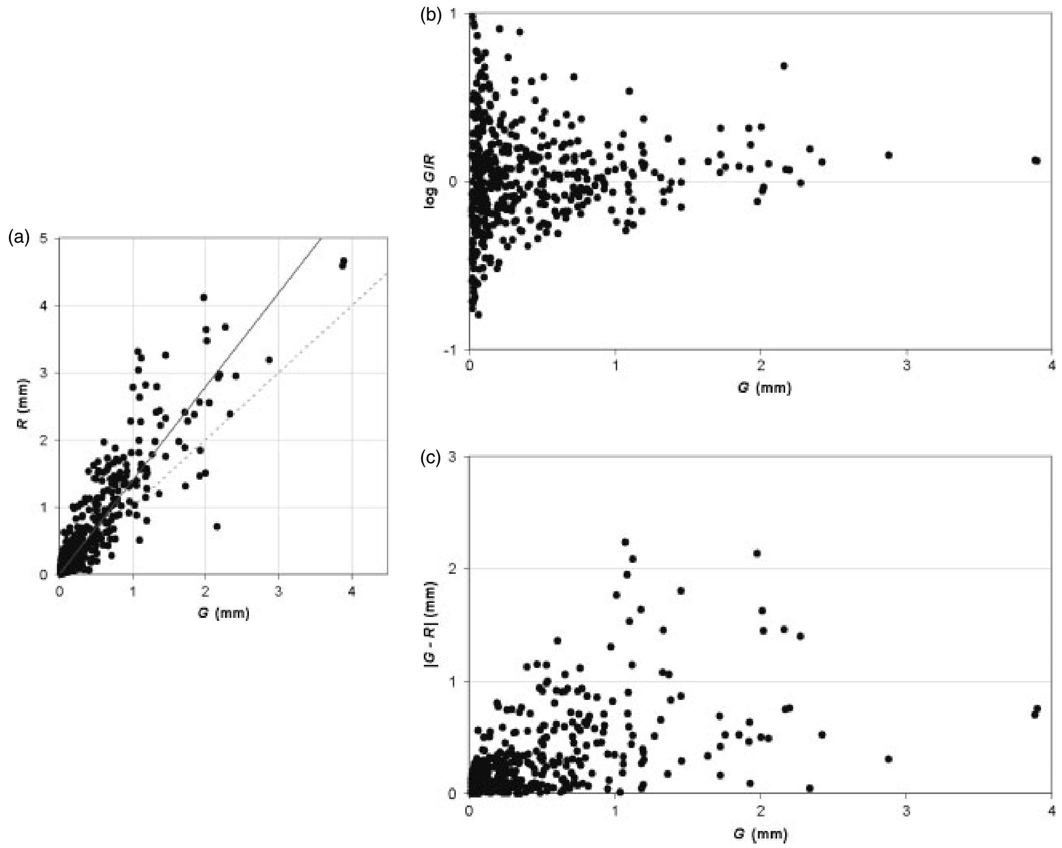

Figure 3. Illustration of radar-raingauge relationship: (a) comparison between rain gauge G and radar R measurements (solid line depicts a linear regression, whereas dashed one represents $R = G$), and dependences of radar errors on rain gauge precipitation using two error definitions: (b) $D = \log(G/R)$, (c) $D = |R - G|$ (Ramża radar data after corrections by NIMROD system, 1 h accumulations from May to September 2006).

whereas radar data are burdened with many errors that have different structure, magnitude and frequency. On the other hand the radar-based data are available with high spatial and temporal resolution over a large area.

The radar data error D may be defined as the difference between radar data R and rain gauge data G, e.g. $R - G$ or G/R or $\log(G/R)$, in radar pixels where precipitation is estimated (practically above a certain threshold, which in this work is taken as 0.5 mm for 1 h accumulations). The radar errors are mostly considered as multiplicative (Germann *et al.*, 2006, 2009), so they are calculated as the ratio on a logarithmic scale of rain gauge data G to radar estimate R. The following definition of the error (in dB) can be employed (Llort *et al.*, 2008; Schröter *et al.*, 2008):

$$D = 10 \times \log_{10}\left(\frac{G}{R}\right) \tag{7}$$

The histogram of such defined errors has a statistical distribution close to normal (Llort *et al.*, 2008), so that the mean value and standard deviation can be determined for each radar measurement. That approach is very useful for statistical processing of the errors (e.g. Schröter *et al.*, 2008).

However, it can be noted that such a definition of radar error D is not optimal for hydrological applications. For instance, in many cases similar values of D can be obtained with this definition, even though big differences between radar and rain gauge precipitation values are observed. Let $G = 1$ mm and $R = 2$ mm for example, so that ratio G/R equals 0.5 and D calculated from Equation (7) equals -3. The case of values $G = 100$ mm and $R = 200$ mm results in exactly the same error D, even though the hydrological meaning of the two cases is extremely different. However, for other applications another definition of radar error may turn out to be more suitable.

In Figure 3 the problem of the choice between the different D definitions is illustrated. Using logarithmic error defined by $\log(G/R)$ the distinct concentration of large errors for low precipitation rates is observed (Figure 3(b)). However, this effect is not observed if error definition $|R - G|$ is used (Figure 3(c)).

Finally, the error definition should depend on the particular application of the *QI* scheme. Since the scheme presented here is mainly prepared for hydrological use, the following definition:

$$D = |R - G| \tag{8}$$

has been employed as the most appropriate. The error is calculated only for radar pixels where rain gauges are located.

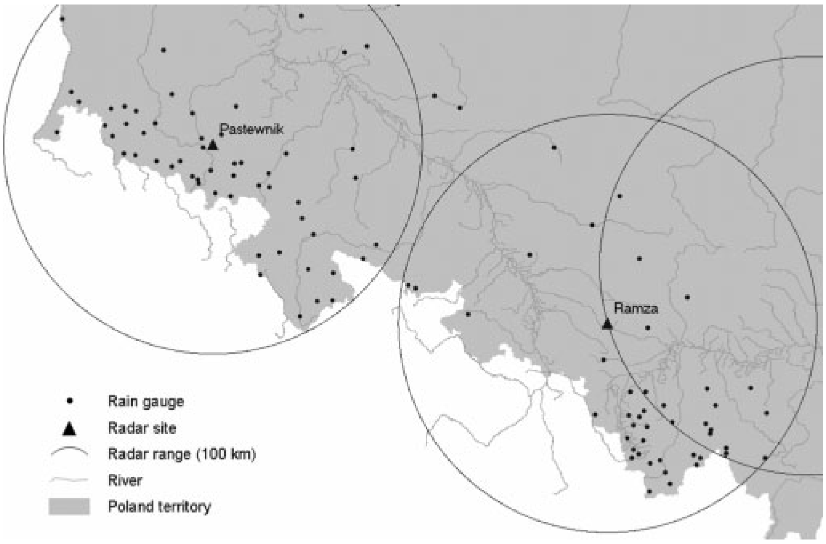

Figure 4. Map of research area: south of Poland with rain gauge and weather radar locations.

3. *QI* scheme parameterization

3.1. Test-bed

The Institute of Meteorology and Water Management (IMGW) is responsible for a national meteorological and hydrological service in Poland. The IMGW collects data from telemetric (meteorological and hydrological) and remote-sensing networks (weather radars, satellite and lightning detection).

For this study an area of hydrological interest has been selected. It is a mountainous region (about 50 000 km^2 in area) in the south of Poland where the upper Vistula (Wisła) and Odra Rivers are the main sources of flood hazard. Telemetric rain gauge data (G) as 1 h accumulations from 107 gauges were collected (Figure 4).

Radar data are provided by the Polish weather radar network POLRAD that consists of eight C-Band Doppler radars (Table II) covering the whole country (Szturc and Dziewit, 2005). They are Gematronik radars with Rainbow software for basic processing of data (Doppler filtering, 2D products generation). The scan strategy used in these measurements is summarized in Table III.

The radar data input to NIMROD as implemented in Poland are provided every 10 min in the form of four PPI (Plan Position Indicator) products at the lowest elevations (Weipert and Pierce, 2003). The following NIMROD corrections are applied to radar data: ground clutter and anaprop (anomalous propagation echoes) removal, vertical profile of reflectivity (VPR) correction and rain gauge adjustment (as mean field bias correction) (Golding, 1998). The main task of the NIMROD is to generate nowcasts up to 6 h ahead.

Characteristics of precipitation data necessary for the scheme parameterization are listed in Table IV. All data employed in the paper were gathered during May to September 2006.

3.2. Estimation of quality function w_i – the relationship between QI_i and X_i

The values of the radar data error D are calculated from historical data set according to Equation (8). The

Table II. Main technical specifications of weather radars of POLRAD network.

Parameter	Value		
Type	Gematronik Meteor 360AC (two radars)	Gematronik Meteor 500 (three radars)	Gematronik Meteor 1500 (three radars)
Frequency	5.4–5.8 GHz (i.e. C-Band)	5.4–5.8 GHz (i.e. C-Band)	5.4–5.8 GHz (i.e. C-Band)
Data types	Z, V, W (Doppler)	Z, V, W (Doppler)	Z, V, W (Doppler)
Transmitter	Coaxial magnetron	Coaxial magnetron	Klystron
Peak transmit power	250 kW	250 kW	250 kW
Raw data depth	4 Bit	8 Bit	8 Bit
Antenna	Parabolic, diameter of 4.2 m	Parabolic, diameter of 4.2 m	Parabolic, diameter of 4.2 m
Antenna gain	45 dBZ	45 dBZ	45 dBZ
Beam width	1°	1°	1°
Pulse repetition frequency (PRF)	250–1200 Hz	250–1200 Hz	250–1200 Hz
Sensitivity	4 dB	4 dB	2 dB
Polarization mode	Linear horizontal	Linear horizontal	Linear horizontal

Table III. Main scan strategy specification used in weather radars of POLRAD network for reflectivity measurements.

Parameter	Value
Number of azimuths	360
Distance from radar	250 km
Distance between measurements along radar beam	1 km
Number of elevations	10
Elevations	0.5°, 1.4°, 2.4°, 3.4°, 5.3°, 7.7°, 10.6°, 14.1°, 18.5°, 23.8°

Table IV. Characteristics of precipitation data produced by IMGW.

Kind of data	*QPM*	*QPE*	*G*
Source	POLRAD network (RAINBOW software)	NIMROD system	Telemetric rain gauge network
Rate/accumulation	Rate and accumulation	Rate and accumulation	1-h accumulation
Spatial resolution	1 km	1 km	Point measurements
Temporal resolution	10 min for rate	10 min for rate	1 h

Table V. Quality functions w_i: relationships between QI_i and X_i values for precipitation data.

Quality factor X_i	Formula
Precipitation rate estimate	
COR (mm)	$QI_{COR} = \begin{cases} 1 & COR \leq 0.774 \\ 1.6546 \times e^{-0.6508 \cdot COR} & 0.774 < COR \leq 10 \\ 0 & COR > 10 \end{cases}$
DR (km)	$QI_{DR} = \begin{cases} 1 & DR \leq 89 \\ -6 \times 10^{-5} \times DR^2 + 7.8 \times 10^{-3} \times DR + 0.7809 & 89 < DR \leq 195 \\ 0 & DR > 195 \end{cases}$
MH (m)	$QI_{MH} = \begin{cases} 1 & MH \leq 550 \\ -4 \times 10^{-7} \times MH^2 + 2.5 \times 10^{-4} \times MH + 0.9834 & 550 < MH \leq 1900 \\ 0 & MH > 1900 \end{cases}$
SV (mm)	$QI_{SV} = \begin{cases} 1 & SV \leq 0.755 \\ 1.534 \times e^{-0.5668 \cdot SV} & 0.755 < SV \leq 10.0 \\ 0 & SV > 10.0 \end{cases}$
TV (mm)	$QI_{TV} = \begin{cases} 1 & TV \leq 1.03 \\ 1.9482 \times e^{-0.6475 \cdot TV} & 1.03 < TV \leq 10.0 \\ 0 & TV > 10.0 \end{cases}$
Precipitation accumulation estimate	
QIS (−)	$QI_{QIS} = QIS$
NP (−)	$QI_{NP} = \begin{cases} 0.1667 \times NP & NP \leq 5 \\ 1 & NP = 6 \end{cases}$

quality of the data is in inverse proportion to D, so the relationships between $(1 - D)$ quantity (normalized to values from 0 to 1) and quality factors X_i are estimated to approximate formulae for particular quality indices QI_i.

For all kinds of precipitation data (see Table IV) the determined formulae $QI_i(X_i)$ are listed in Table V and presented in Figures 5 and 6 as diagrams.

The threshold values X_{i0} and X_{i1} for each QI_i result from formulae determined there (see Table V).

The following assumption is made to estimate the X_{crit} values: quite poor radar measurements of surface precipitation are taken for a distance *DR* above 200 km, that corresponds to *MH* higher than 3.7 km for flat terrain. The critical values of the other quality factors have been arbitrary based on analyses of their extreme values. The critical values for all quality factors are listed in Table VI.

3.3. Weights for particular quality indices QI_i

The next step is a determination of weights W_i for all quality indices QI_i (Equation (5)), that should be performed on historical dataset. The weights W_i of particular quality factors X_i depend on their correlations with radar data error D, that is calculated from differences between rain gauge G and radar R observations in rain gauge locations (Equation (8)).

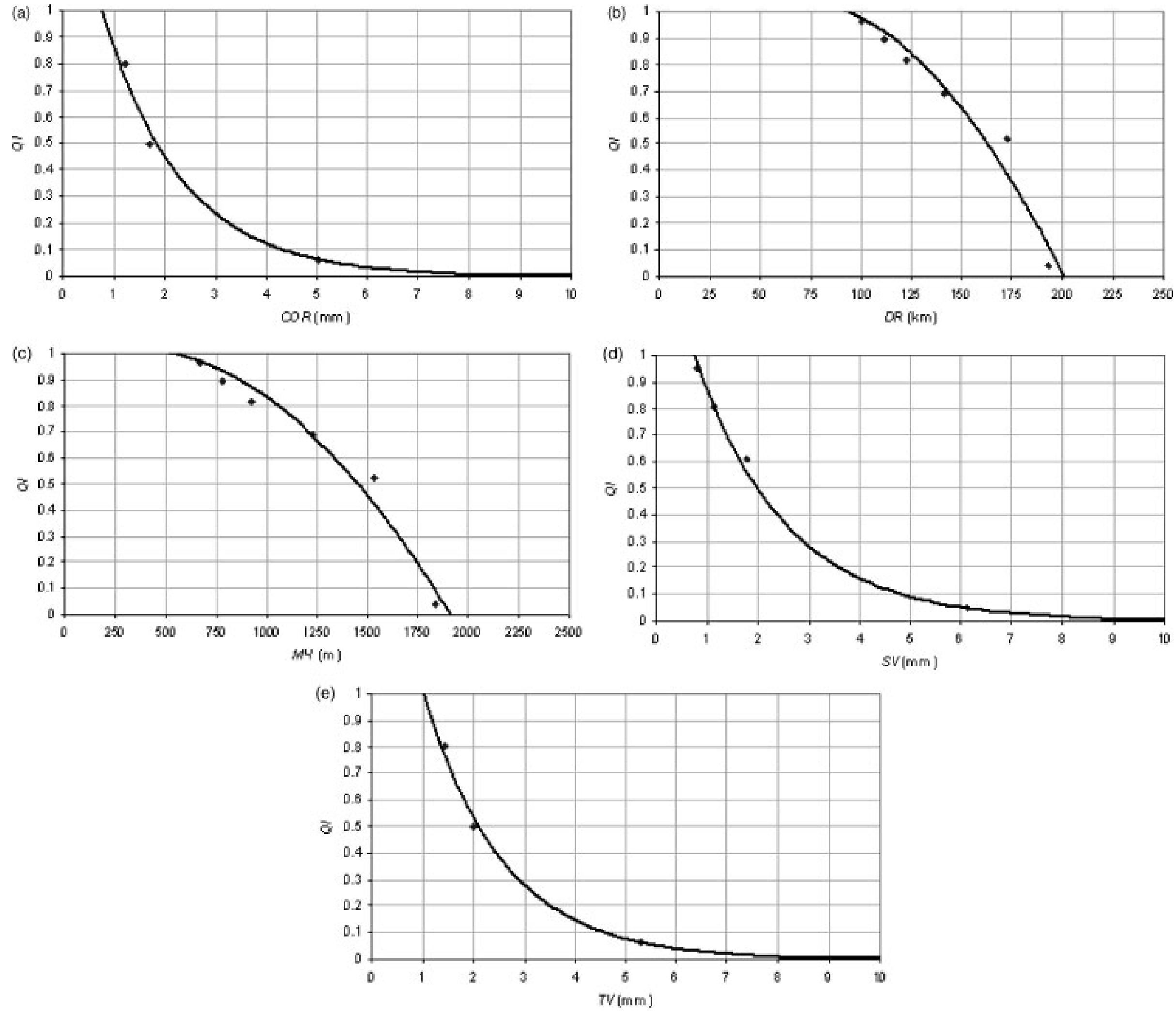

Figure 5. Diagrams of relationships between QI_x and X_i values for (a) *COR*, (b) *DR*, (c) *MH*, (d) *SV*, and (e) *TV* for precipitation rate estimate.

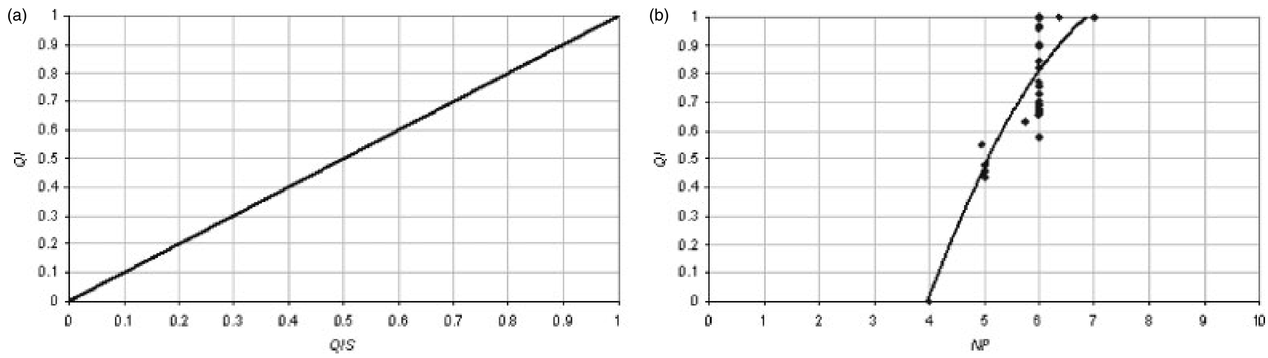

Figure 6. Diagrams of relationships between QI_x and X_i values for (a) *QIS* and (b) *NP* for precipitation accumulation estimate.

Therefore, the correlation coefficients r_i between the given quality factor X_i values and radar data errors D constitute a basis for determination of the weights W_i. It is assumed that the weights are in proportion to relevant correlation coefficients and should be normalized to one (i.e. their sum has to equal one). Results of the weights' calculation are presented in Table VII. It has been decided that for rate products both weight sums of static (*DR* and *MH*) and dynamic (*COR, SV*, and *TV*) factors equal 0.5. Having determined the weights W_i, Equation (5) can be applied to calculate the final quality index *QI* for radar-based precipitation rate.

3.4. Example of quality fields

In Figure 7 an example of the set of the quality fields for selected event is presented. The precipitation field is rain rate estimate from 5 August 2006, 0300 UTC,

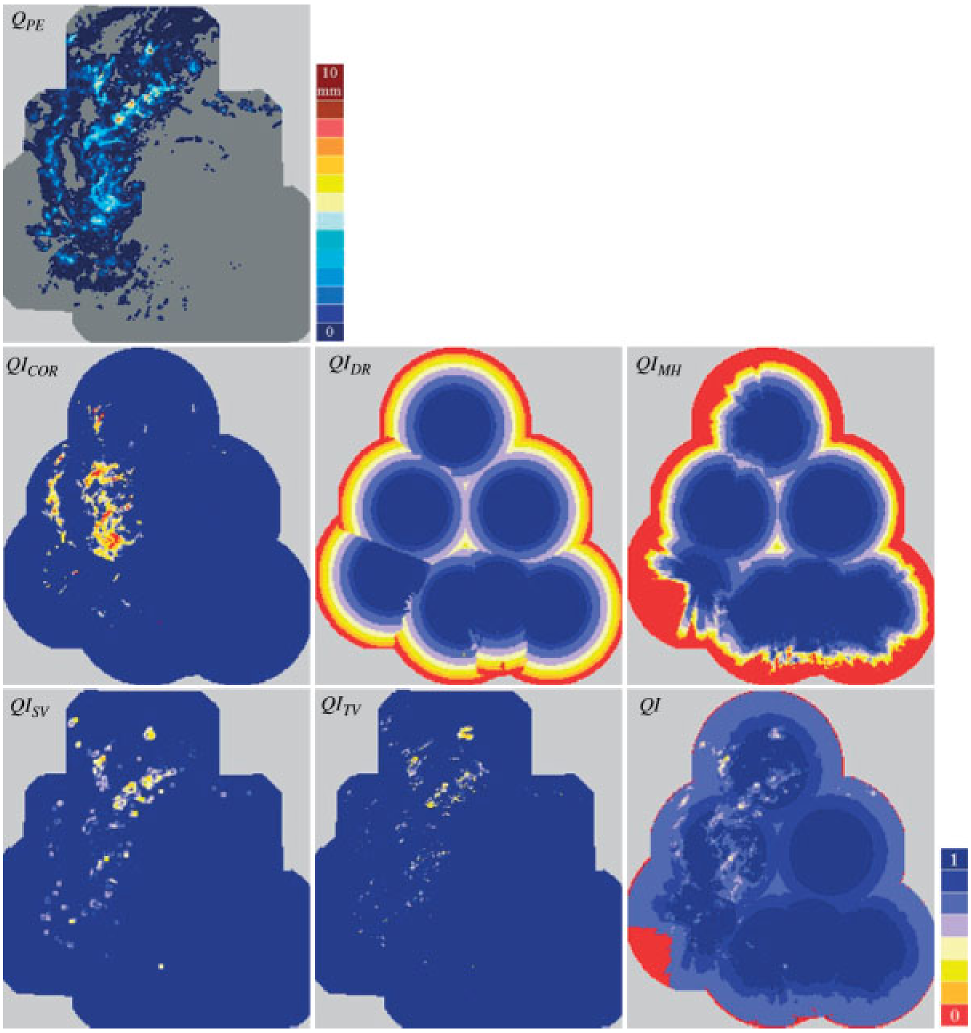

Figure 7. Example of quality indices *QI* for precipitation rate estimate from 5 August 2006, 0300 UTC (when 7 out of 8 weather radars were running): *QPE* (radar corrected data), QI_{COR}, QI_{DR}, QI_{MH}, QI_{SV}, QI_{TV}, and resulting averaged *QI*.

Table VI. Critical values of all quality factors for radar-based data.

Quality factor X_i	Units	$X_{i\text{crit}}$
COR	mm	15.00
DR	km	200
MH	m	3700
SV	mm	10.00
TV	mm	15.00
QIS	–	–
NP	–	1

Table VII. Absolute correlation coefficients $|r_i|$ and weights W_i of all quality factors X_i for different kinds of precipitation data.

Quality factors X_i	Correlation coefficient $\|r_i\|$	Weight W_i (of QI_i)
Precipitation rate estimate		
COR	0.889	0.162
DR	0.426	0.275
MH	0.349	0.225
SV	0.940	0.172
TV	0.911	0.166
Precipitation accumulation estimate		
QIS	0.954	–
NP	0.505	–

when seven out of eight POLRAD weather radars were running. A set of all particular quality indices QI_i and final quality index *QI* map were computed for this event.

It can be noted that the fields QI_{COR}, QI_{SV} and QI_{TV} follow the pattern of the precipitation field to some degree. This is because the three factors are related to the precipitation field (they can be high if the precipitation is relatively high). The two next fields QI_{DR} and QI_{MH} are static if the set of working radars is constant.

The final quality index *QI* map for this event is presented as the bottom right image in Figure 7. The map shows the final result of *QI* calculation using the proposed scheme. It can be noted that the quality depends on all quality factors included in the scheme (see Table I). The most significant factors are height of the lowest radar beam (*MH*), especially for places at longer distances to

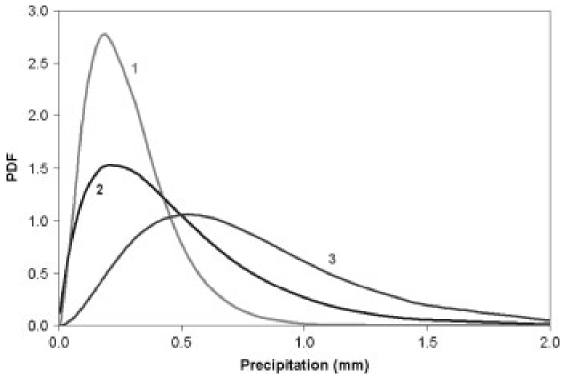

Figure 8. Example of gamma PDF. 1: $p = 3.9$, $b = 10.0$; 2: $p = 2.9$, $b = 4.0$; 3: $p = 4.1$, $b = 4.0$.

the nearest radar and in mountainous areas (south of the maps), and precipitation field variability, both spatial (SV) and temporal (TV) that are related.

4. Probabilistic precipitation estimate basing on *QI* information

Anomalies in weather radar data, such as ground clutter, anaprop and external transmitters, often interfere with precipitation echoes. Due to the complicated structure of the measurement errors it is more convenient to consider the errors as partly having a probabilistic nature (Peura *et al.*, 2006). As a result, in the present study radar-based precipitation can be treated as a probabilistic quantity. Peura and Koistinen (2007) stated that defining quality index as closely as possible to a probabilistic framework is advantageous by easier mathematical form and clear information for end user.

Having a quality index *QI* map for radar-based precipitation data, the next step is to express the precipitation field in a probabilistic form, in which uncertainty results from the *QI*. It is proposed to take account of the uncertainty using some PDF (probability density function) to describe the precipitation. Parameters of the PDF can be determined from *QI* applying the algorithm described below (Szturc *et al.*, 2008b). However, first the specific PDF suitable to reflect physical features of rainfall should be selected.

The gamma distribution (see Figure 8) seems to be appropriate (e.g. Amburn and Frederick, 2006, 2007):

$$PDF(x) = \frac{b^p}{\Gamma(p)} x^{p-1} \mathrm{e}^{-bx} \tag{9}$$

where p and b are the gamma PDF parameters, $p, b > 0$; Γ is the gamma function.

The two gamma PDF parameters are estimated for each data pixel separately based on the *QI* map attached to the radar-based data. As radar errors are correlated in space and time, then the PDF is conditional on errors in the neighbourhood of each pixel. This seems to be more suitable to characterize radar errors than one individual PDF for each radar pixel (e.g. Germann *et al.*, 2009). However, such a conditional PDF as well as alternatively the full error covariance matrix (Germann *et al.*, 2009) are difficult to use in practice.

The PDF calculated from *QI* data can be considered as correlated in space and time since the *QI* follows the precipitation field pattern. The relationships of the parameters p and b of the gamma PDF of random variable X, with statistical moments expectation $\mathrm{E}(X)$ and variance $\mathrm{var}(X)$ are as follows:

$$\mathrm{E}(X) = \frac{p}{b};\ \mathrm{var}(X) = \frac{p}{b^2} \tag{10}$$

From the above equation system both parameters p and b can be determined:

$$p = \frac{\mathrm{E}^2(X)}{\mathrm{var}(X)};\ b = \frac{\mathrm{E}(X)}{\mathrm{var}(X)} \tag{11}$$

Therefore, two statistical moments of the gamma PDF (Equation (10)) must be determined in order to solve the equation system (Equation (11)). It is assumed that $\mathrm{E}(X)$ equals the radar deterministic measurement R, and $\mathrm{var}(X)$ is in proportion to the data error D. The error is indirectly determined for each radar pixel from quality index *QI* as a quantity proportional to $(1 - QI)$. This expression is a unitless quantity within the range between 0 and 1, so that it must be adjusted to magnitude of actual precipitation R. The proposal is to calculate an error D' from:

$$D' = R(1 - QI) \tag{12}$$

meaning that radar errors are limited by a factor 2 (Mittermaier, 2008). However, under some circumstances it might be a strong assumption (for instance attenuation when using C-band radar). Therefore the variance of variable X is proportional to D' and can be written in the form:

$$\mathrm{var}(X) = a_1 \cdot R(1 - QI) + a_2 \tag{13}$$

where a_1, a_2 are taken as follows: $a_1 = 1$, which means that radar errors are still limited by a factor 2, and $a_2 = 0.1$ mm, that is the lowest significant value of precipitation. As a result:

$$\mathrm{var}(X) = R(1 - QI) + 0.1 \tag{14}$$

The range of the variance is between 0.1 mm and $(R + 0.1)$ mm.

Finally, for a given data pixel with known *QI* and R values both p and b parameters can be calculated from the equation system:

$$p = \frac{R^2}{R(1 - QI) + 0.1};\ b = \frac{R}{R(1 - QI) + 0.1} \tag{15}$$

In this way the precipitation PDF can be computed for each data pixel.

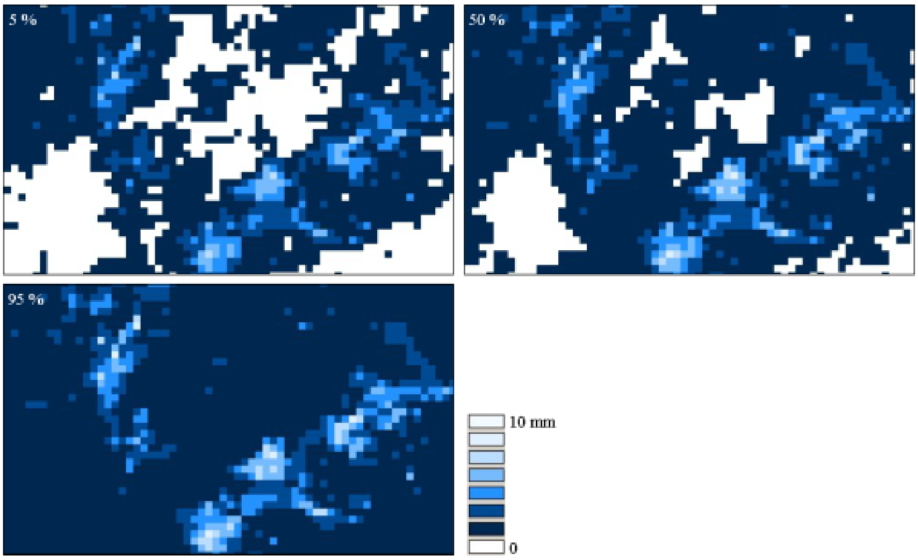

Figure 9. Example of precipitation percentiles from 5 August 2006, 0300 UTC: 5, 50 and 95%. This figure is available in colour online at wileyonlinelibrary.com/journal/met

Having the PDF, the ensemble of the precipitation fields can be generated as percentiles of the PDF (Szturc *et al.*, 2008b). The approach makes it possible to deal with perturbations in radar images and to employ a probabilistic input to hydrological rainfall-runoff models. In Figure 9 an example of set of precipitation percentiles is shown for fragment of the field from Figure 7. In the case of the lowest percentiles the estimated precipitation is treated as if it was an overestimate, so the values are significantly reduced in comparison to estimated ones. For the highest percentiles the relation is opposite, thus underestimation is assumed. The 50% percentile reflects the estimated precipitation pattern.

5. Summary and conclusions

The *QI* scheme proposed in the paper, with a specific set of quality factors X_i and formulation, may be one of many possible realizations of such a scheme, so it can be treated as a subjective one. The final form of the scheme depends on specific implementation and the proposed *QI* scheme must be adopted to each particular realization.

The proposed scheme has been developed bearing in mind first of all the feasibility of its implementation in real-time. In consequence the required information must be available online. On the other hand, the scheme is expected to take account of contribution of the most important perturbing factors in total uncertainty in proper proportion. Moreover, radar-based data and related errors are variable in space and to a lesser degree in time, so the quality index should characterize the data uncertainty in each pixel of precipitation maps.

The quality index *QI* scheme provides users of radar-based data with information about the data quality. What is more, the quality information may constitute a useful starting point to generate probabilistic precipitation fields by introducing precipitation PDFs. Probabilistic description of the precipitation phenomenon is commonly found to be one of the most important challenges in radar meteorology and hydrology (COST 731, 2004). The precipitation field ensemble generated basing on quality information can be used as input to hydrological rainfall-runoff model (e.g. Komma *et al.*, 2007; Germann *et al.*, 2009). The data uncertainty can be taken into consideration quantitatively in this manner.

The scheme presented in the paper was implemented in 2009 for precipitation data from the Polish weather radar network POLRAD after processing by the NIMROD system. It has been working operationally in Ground-Based Remote Sensing Department of IMGW to deliver information about the data quality to the data users.

At present the POLRAD network is being modernized by upgrading to dual-polarimetric radars. At the beginning of 2010 the first radar upgrade was implemented, and the others are planned to be upgraded successively. After completion of the modernization the quality index scheme will be developed further, especially by introduction of additional quality factors and more advanced algorithms. The most important factors to be included are radar beam attenuation in precipitation and melting layer existence.

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