Radar and Station Measurement Tresholds for More Accurate Forecast of Convective Precipitation

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***Abstract*— This article is focused on the evaluation of the accuracy of measured values from radar and station precipitation measurements in order to determine their threshold limits. The methodological part presents the definition and practical use of the CAPPI, VIL and ETOP radar products, including the SUM MERGE combined product. The resulting part is aimed on the assessment of average of the measured values and their accuracy in historical situations connected with the occurrence of convective precipitation of weak and strong intensity, especially for western and northern directions movement, and for all directions without western and northern directions, respectively. The goal is to set thresholds that will be used to configure an algorithm for converting input data from these products in order to compute the statistical and nowcasting prediction of convective precipitation.**

Keywords – atmospheric convection, convective precipitation, radar precipitation measurement, data conversion, crisis management, flood protection measures

I. INTRODUCTION

At present, flash floods are one of the most common natural disasters that often affect by their negative impacts the society not only in the Czech Republic but also in the world. The more frequent and intense occurrence of this phenomenon is very likely due to the current climate change, which results in an increase in the surface air temperature and especially the moisture in the atmosphere. [1], [2], [3]. As a result, this dangerous hydrometeorological phenomenon more often occurs unevenly, unexpectedly with a local occurrence [4], which is also due to the nature of heavy convective precipitation as one of the main causal factors of flash floods. Heavy convective precipitation with intensity above 30 mm/hour. occurs in strong convective storms, which may be accompanied by further dangerous phenomena such as hail, strong wind gusts and tornadoes [2], [5], [6], [7]. These phenomena can cause significant damage to the property of the population and the state infrastructure and, in particular, can adversely affect the health and lives of the population in the area. [2], [7]. Therefore, it is very important to carry out research to ensure timely and more accurate information on the occurrence of these events, which will be of particular benefit to crisis management authorities for the purpose of preparing and implementing preventive measures to mitigate the effects of heavy convective precipitation. The main purpose is to minimize damage to the lives and health of the population, property and other society interests.

Forecasting of convective precipitation is one of the most complex problems in the current meteorology not only in the Czech Republic, but also worldwide. The accuracy and quality of predictive information on these local phenomena is one of the most significant conditions for decision-making support of the region's crisis management authorities. National meteorological institutions generally prepare forecasts by three basic approaches, whereas the first two methods are also adopted in forecasting practice in the Czech Republic. The first approach is weather forecast as a result of numerical modeling [8], [9], [10] which are applied operatively in practice as a support tool for nowcasting methods. The main shortcomings of this method stem mainly in the use of the system of convection parameterization equations, because, in principle, they go not provide sufficiently high-quality predictive information on the future occurrence and development of convective precipitation. Another problem with the prediction of convective precipitation is that numerical models do not consider local conditions as well as local orography due to the large amount of data. For this reason, nowcasting methods are used more often as a second approach. They provide a very short-term precipitation forecast based on radar echo extrapolation methods [11], [12], [13]. The main disadvantage of the nowcasting method is that it cannot predict the life cycle of convective cells. The main reasons are insufficient possibilities of remote detection of the dynamic variability of the rainfall field, including local conditions of convection initiation as well as in numerical models. Another major shortcoming is the very short length of the forecast, about 60 minutes, which is a completely insufficient length of the forecast for the implementation of preventive and preparatory measures.

For these reasons, a pilot research project was proposed, the aim of which is to specify information on the future occurrence of convective precipitation in the territory of municipalities with extended powers in the Czech Republic and in the Zlín Region. The prediction of convective precipitation will be solved using algorithms of statistical and nowcasting prediction of convective precipitation. More accurate forecast of convective precipitation will be computed for 206 municipalities with extended powers in the Czech Republic and nowcasting forecast for only 13 municipalities with extended powers of the Zlín Region for historical situations for a period of years of 2007-2020. The length of the statistical forecast of convective precipitation will be chosen from 3 to 12 hours for operational use; and from 15 to 24 hours for orientation use in practice. Nowcasting forecast using the X-band radar of the Zlín Region will operate with a forecast length of 1 to 3 hours, also taking the advantage of the statistical analysis of historical situations, which will be the core of both algorithms. The aim of this analysis will be to select one or more historical situations on the basis of comparative-selective criteria, which will best correspond to the situation associated with the occurrence of predicted convective precipitation. Subsequently, partial forecasts of statistical analysis will be calculated on the basis of data of radar and station measurement products from C-band radars of the CZRAD network for the territory of the Czech Republic and radar products of the X-band radar of the Zlín Region. Partial predictions will be a statistical estimate of the probability of convective precipitation and the risk of flash floods. These outputs will be generated in map outputs with a range of values from 0 to 3 [2] based on threshold intervals of radar and station products. Studies focused on the research of threshold limits of radar products for the detection of convective precipitation and dangerous accompanying phenomena have been investigated in foreign and local studies [17], [18], [19].

II. METHODS

As already mentioned in the Introduction section, the main outputs of the project are applications for statistical and nowcast prediction of convective precipitation. Both algorithms have a common phase, which is statistical analysis of historical situations. The aim of the statistical analysis is to select one or more historical situations according to comparative-selective attributes, which are:

- Direction and speed of the precipitation system - given by the direction of the wind at 600 hPa and the Corfidi vector of storm movement.
- Storm tracks - determines the spatial frequency of convective precipitation distribution in a more local scale of a given direction of precipitation movement.
- Time of occurrence of convective precipitation - time determination of the occurrence of convective precipitation in three-hour intervals.
- Type of convective precipitation - determination of frontal or non-frontal (quasi-frontal, orographic) convective precipitation.

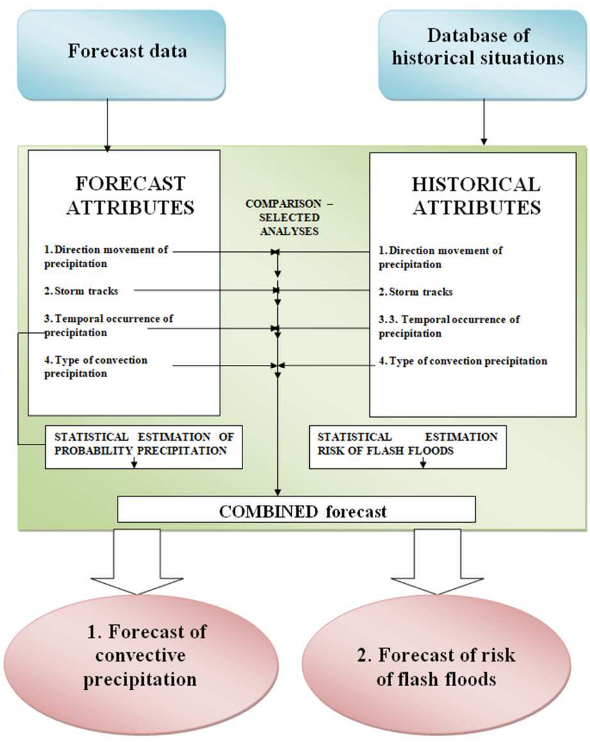


Figure 1. Scheme of algorithm of the statistical analyses of historical situations connected with convective precipitation

If the selection of historical situations is completed and specific historical situations are determined that best correspond to the predicted situation, then a statistical estimate of the probability of convective precipitation or the risk of flash floods is calculated based on computational attributes. These attributes are the outputs from radar and station precipitation measurements, which are the CAPPI and VIL radar products obtained from C and X-band radar, and the combined product 1 hour SUM MERGE gained from C-band radar. For the purposes of performing the calculation using these attributes, it was necessary to analyze the outputs from the measurement of convective precipitation and set their threshold limits. The following subchapters focus on the analysis of these products.

A. CAPPI radar product

Plan Position Indicator (PPI) is one of the most elementary radar product: radar data are obtained from a complete rotation of radar with a fixed elevation angle. The Constant Altitude Plan Position Indicator (CAPPI) is a slice through the data volume at a user-defined altitude or height above the Earth's surface. It requires PPI scans at multiple elevation angles. The CAPPI product is composed of data from each elevation that is requested at the selected altitude for the cross-section. The reflectivity in a given pixel is calculated by a trilinear interpolation: it starts with a bilinear interpolation between the nearest radar shots like in the PPI product, but there is also one more interpolation between the nearest elevations.

The output of this product is the measured radar reflectivity Z [dBZ], which defines the amount of energy reflected from the precipitation cloud particles, where N (D) denotes the particle size spectrum and Di represents the droplet diameter [2], [5], [16]:

$$Z = \int N(D) D^6 dD \quad (1)$$

The measured radar reflectivity Z_e is shown as $10\log Z_e$ [mm^6/m^3] in units of dBZ.

Rainfall intensity I depends on radar reflectivity Z. Radar reflectivity Z is calculated by the Marshall-Palmer relation:

$$Z = aI^b \quad (2)$$

where a and b are experimentally determined constants (a - 200, b - 1.6). The precipitation intensity I is calculated according to the following formula [2], [5], [16]:

$$I = 10(Z\text{-}10\log(a))/10b \quad (3)$$

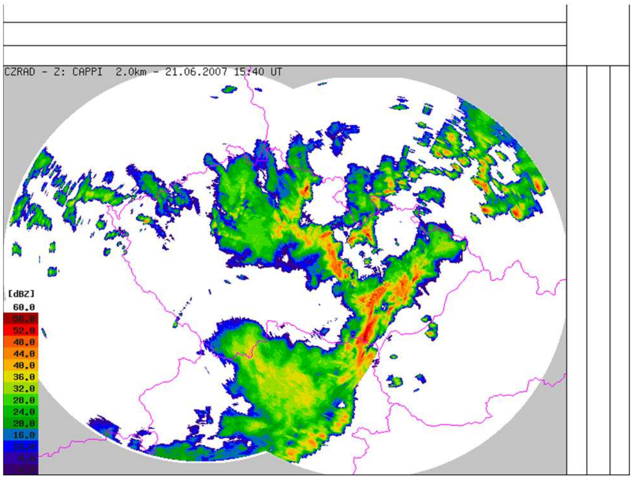


Figure 2. CAPPI 2 km radar product [15]

In predictive practice on (Figure 2), the CAPPI radar product is used for levels of 2 km and below and represents the amount of precipitation that has actually fallen on the Earth's surface. For this reason, it will be used for statistical estimation of the probability of occurrence of convective precipitation in both algorithms. This product is significantly more accurate than other radar products such as ColumnMax (termed also as Max Z), which is the maximum intensity of precipitation detected in the entire vertical of the troposphere [2], [5], [16].

B. VIL radar product

The Vertically Integrated Liquid (VIL) product represents the sum of water amount within the column above the particular place of ground, expressed in kg/m^2. The VIL value can be regarded as an indicator of the potential rainfall. VIL is usually estimated on the basis of known reflectivity:

$$VIL = 3{,}44.10^{-6} \int_{h_z}^{h_t} Z^{4/7} dh \quad (4)$$

where Z [mm^6.m^{-3}] is the radar reflectivity, h_z [m] is the height of the cloud base and h_t [m] is the height of the upper cloud boundary. In the calculations for each area element, the summation is performed over the individual PPI levels.

The so-called Z-M relationship is used that relates the rainfall rate M with the radar reflectivity Z through an empirical formula where the constants usually reflect raindrop size, their fall speed, and the overall conditions for the rainfall genesis within a particular geographic/climatic region, respectively [2], [5], [16].

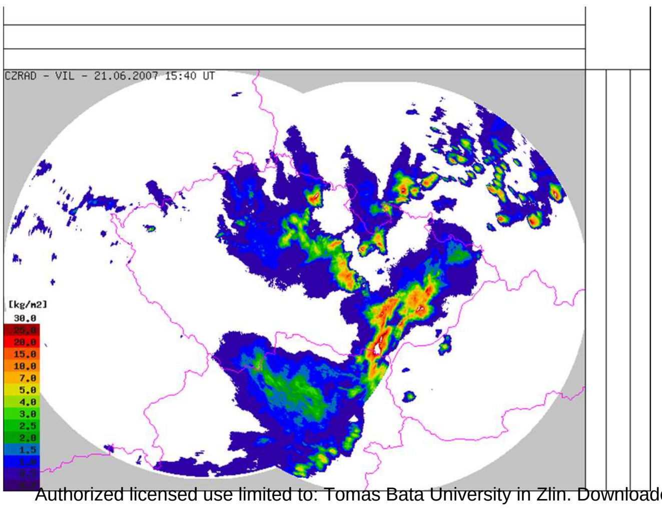


Figure 3. VIL radar product [15]

As can be seen in Figure 3, this product is primarily intended for estimating the occurrence of very intense convective precipitation (torrential rainfall) that is primarily used for statistical estimation of the risk of flash floods.

C. ETOP radar product

The radar product ETOP (also termed as Echo-Top) provides information about the vertical extent of clouds in km, expressed as a height, in which the radar reflectivity is higher than a defined threshold (Figure 4):

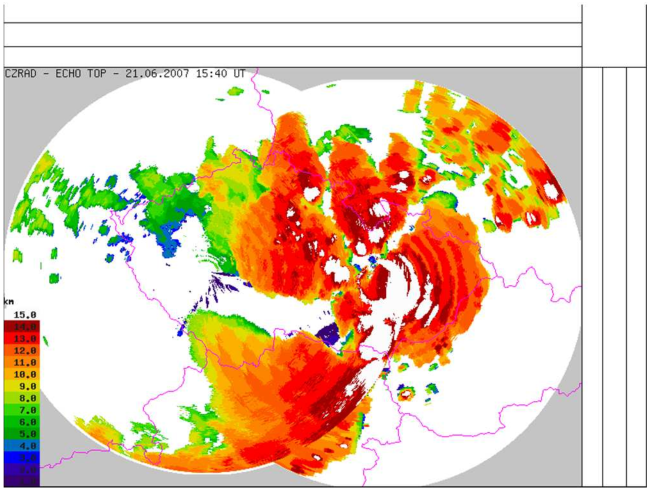


Figure 4 ETOP radar product [15]

This product provides supporting information on the vertical development of the convective storm for CAPPI and VIL products [2], [5], [16].

D. SUM MERGE combined product

The combined product 1 hour SUM MERGE presents the summarized value estimated precipitation using meteorological radars of the CZRAD network and ground station precipitation measurement. The outputs of this product are calculated using interpolation methods:

- Method of Inverse Distance Weighting (IDW).
- Kriging methods [20], [21].

Interpolation is performed using autocorrelation analyzes. It is an analysis of measured values with respect to measurement errors in relation to previous outputs, on the basis of which a new value of measured precipitation is calculated.

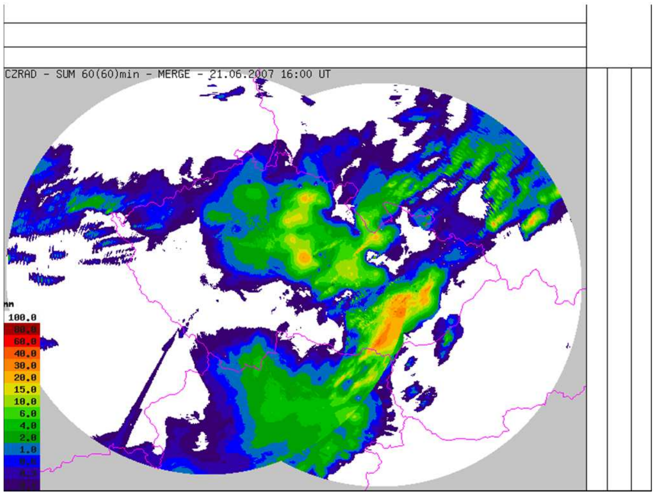


Figure 5.SUM MERGE combined product [14]

Figure 5 shows the combined SUM MERGE product. It provides information on the currently measured precipitation from the ground-based network of precipitation measuring stations, which is supplemented by the estimation of precipitation from radar measurements. As this product best expresses the real measured state of precipitation, it is used to calculate a statistical estimate of the probability of precipitation and the risk of flash floods [2], [5].

III. Results

This chapter focuses on the evaluation of the outputs of radar and station (combined) products in order to determine their threshold limits expressed in the range of coefficients from 0 to 3. These outputs will be applied in the conversion data-mining algorithm of these products and subsequently for the calculation of a statistical estimate of the probability of convective precipitation and the risk of flash floods.

The evaluation of product thresholds is divided according to the directions of movement of precipitation system (1st attribute):

- All directions movement of precipitation without western and northern direction.
- Western and northern directions of precipitation.

A. Product thresholds for all flow directions without western and northern direction od precipitation movement

Threshold limits for the CAPPI, VIL and ETOP radar products, including the SUM MERGE combined product, were set for the following directions of precipitation with a typically higher intensity of precipitation than for the western and northern direction:

- Southwestern (SW),
- South (S),
- Southeast (SE),
- Eastern (E),
- Northeastern (NE),
- Northwestern (NW) [2].

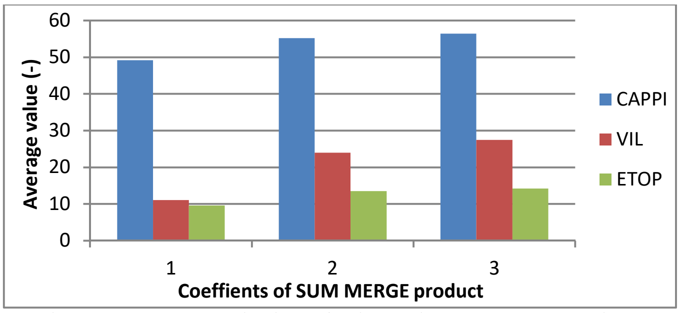
The first evaluated output is the SUM MERGE combined product, which best expresses the measured amount of precipitation from ground meteorological stations supplemented by radar measurements.

In the first phase, the scale for this product is determined by an expert estimate based on the classification of the dangerous phenomenon "Storm" of the Integrated System of Warning Service of the Czech Hydrometeorological Institute (CHMI) according to Table 1:

TABLE I Coefficients Of Rainfall Intensity Of Sum Merge

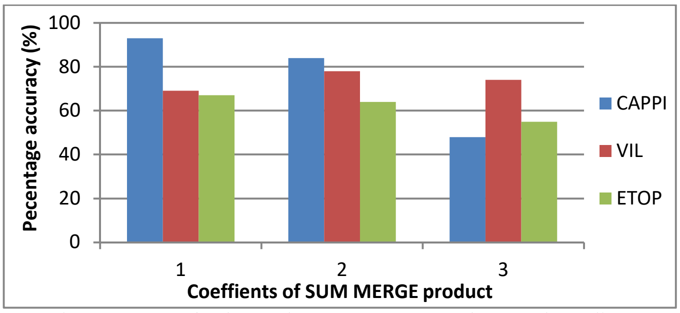
Coefficients	**0**	**1**	**2**	**3**
Rainfall intensity level	***Greatly weak***	***Moderate***	***Slightly strong***	***Strong (greatly, extremely)***
Rainfall intensity (mm/hr.)	0-3	4-14	15-29	above 30
Probability of occurrence (%)	0-0.24	0.25-0.49	0.50-0.74	0.75-1.00
Risk of flash floods	Very low	Low	High	Extremely high

Table 1 presents the relationship between the numerical value of precipitation intensity, their partial outputs of the statistical estimate of the probability of convective precipitation and flash flood risk and their converted values in the form of coefficients from 0 to 3. These coefficients serve the purpose of conversion to a uniform dimensionless number format.



Graph 1. Average measured values of radar products CAPPI, VIL and ETOP depending on coefficients of SUM MERGE product for all but western and northern air flow

Graph 1 represents the results of the average values obtained from the measurement of convective precipitation by the radar products CAPPI, VIL and ETOP. The best measured average values of the CAPPI product were achieved for coefficients 1 with a value of 49,2 dBZ. On the contrary, less satisfactory results were obtained for the coefficient 3, where the average measured value was 4 dBZ lower than the proposed threshold limit due to the small number of evaluated situations and measurement errors resulting from the nature of convective precipitation. The VIL product had an analogous development trend with the lowest value of 27.5 kg / m^2 for the category with the index of 3. The ETOP product achieved slightly better average values than the previous two products. The main differences between the products were due to the measurement of local convective precipitation.



Graph 2 Accuracy of radar products CAPPI, VIL and ETOP depending on coefficients of SUM MERGE product for all but western and northern air flow

As can be seen in Graph 2, the highest average accuracy was attained for CAPPI and VIL products. On the other hand, the ETOP product achieved approximately 20-30 % lower accuracy due to the bias of the results when measuring local convective precipitation in terms of evaluating the results of the spatial distribution of convective precipitation. The resulting output of the configuration of the values of the coefficients of the radar products and the SUM MERGE combined product is shown in Figure 6:

Coeff.&hexa code		Radar measurement			Station measurement	
RANK (COEFF.)	COLOR	CAPPI	VIL	ETOP	RANK (COEFF.)	SUM MERGE
0	#eef3fa	0	0	0	0	0
0	#380070	4	0,2	1	0	0,1
0	#3000a8	8	0,5	2	0	0,3
0	#0000fc	12	1	3	0	0,6
0	#006cc0	16	1,5	4	0	1
0	#00a000	20	2	5	0	2
0	#00bc00	24	2,5	6	0,5	4
0	#34d800	28	3	7	1	6
0	#9cdc00	32	4	8	1	10
0	#e0dc00	36	5	9	2	15
0	#fcb000	40	7	10	2	20
0,5	#fc8400	44	10	11	3	30
0,5	#fc5800	48	15	12	3	40
1	#fc0000	52	20	13	3	60
2	#a00000	56	25	14	3	80
3	#fcfcfc	60	30	15	3	100

Figure 6 Final configuration of threshold limits of radar and station measurement of convective precipitation for all but western and northern directions

Figure 6 presents the setting of CAPPI, VIL and ETOP radar product values according to the SUM MERGE product. At the same time, hexadecimal color codes are assigned to the individual coefficients, which are read from the input images of these products. This configuration is implemented in a conversion algorithm for the purpose of data mining to convert the pixel values of radar products to a uniform format of coefficients from 0 to 3 (a value of 0.5 corresponds to a value of 1). These values are used to compute the partial and main outputs in the statistical and nowcasting forecast algorithms.

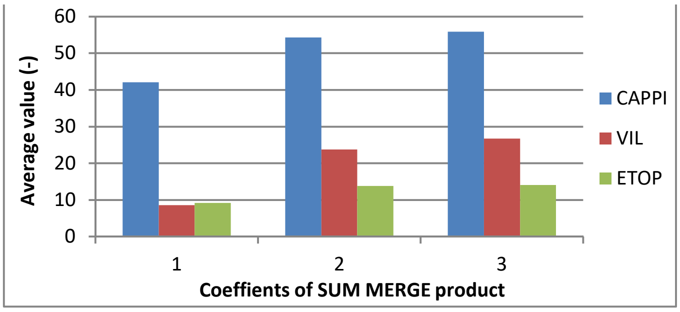
B. *Products tresholds for western and nothern precipitation movement*

Threshold limits for the CAPPI, VIL and ETOP radar products, including the combined product SUM MERGE, were set only for the western and northern directions of precipitation movement with a characteristically lower intensity of precipitation than for other flow directions.

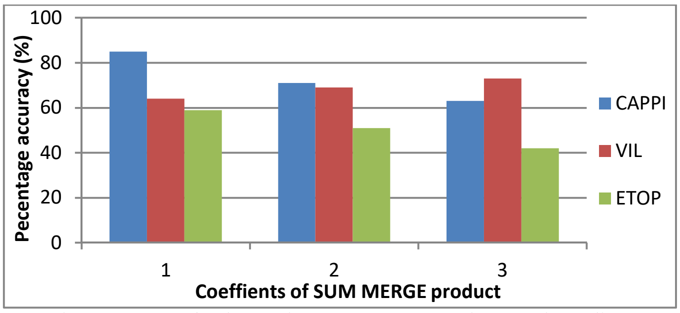
The first evaluated output is a combined product of 1 hour SUM MERGE with adjusted values of rainfall intensity according to Table 2:

TABLE II. COEFFICIENTS OF RAINFALL INTENSITY OF SUM MERGE

Coefficients	0	1	2	3
Rainfall intensity level	***Greatly weak***	***Moderate***	***Slightly strong***	***Strong (greatly, extremely)***
Rainfall intensity (mm/hr.)	0-1	2-14	15-29	above 30
Probability of occurrence (%)	0-0,24	0,25-0,49	0,50-0,74	0,75-1,00
Risk of flash floods	Very low	Low	High	Extremely high



Graph 3 Average measured values of radar products CAPPI, VIL and ETOP depending on coefficients of SUM MERGE product for with western and northern air flow



Graph 4 Accuracy of radar products CAPPI, VIL and ETOP depending on coefficients of SUM MERGE product for with western and northern air flow

Graphs 3 and 4 show an analogous trend in the development of measured values of all radar products with the only difference that slightly lower threshold limits were reached due to lower intensity of convective precipitation. A more significant difference is evident in the percentage accuracy of the measured values of radar products depending on the SUM MERGE combined product, especially for the product ETOP, which achieved the lowest accuracy.

Figure 7 illustrates the configuration of the threshold limits for western and northern directions with a shifted precipitation intensity threshold:

Coeff.&hexa code		Radar measurement			Station measurement	
RANK	COLOR	CAPPI	VIL	ETOP	RANK	SUM MERGE
0	#eef3fa	0	0	0	0	0
0	#380070	4	0,2	1	0	0,1
0	#3000a8	8	0,5	2	0	0,3
0	#0000fc	12	1	3	0	0,6
0	#006cc0	16	1,5	4	0	1
0	#00a000	20	2	5	0,5	2
0	#00bc00	24	2,5	6	0,5	4
0	#34d800	28	3	7	1	6
0	#9cdc00	32	4	8	1	10
0	#e0dc00	36	5	9	2	15
0,5	#fcb000	40	7	10	2	20
0,5	#fc8400	44	10	11	3	30
0,5	#fc5800	48	15	12	3	40
1	#fc0000	52	20	13	3	60
2	#a00000	56	25	14	3	80
3	#fcfcfc	60	30	15	3	100

Figure 7 Final configuration of threshold limits of radar and station measurement of convective precipitation only for western and northern directions

IV. CONCLUSION

The aim of this article was to provide information on radar and combined products for estimating convective precipitation in terms of configuring their thresholds for their conversion analysis.

The core part of the article contained the evaluation of the configuration of the threshold limits of the precipitation measurement products for all but the western and northern directions of precipitation movement; the second part only for the western and northern directions. This division was made due to the different nature of the intensity of convective precipitation, especially for the second group of directions. The western and northern directions of precipitation movement occur very often on weak cold or occlusal fronts connected with low-pressure areas above northern or northwestern Europe, or during cold advection as quasi-frontal precipitation within the cold instable air mass. Convective precipitation usually moves very fast and does not reach too high intensities, and therefore there is usually no risk of flash floods. Consequently, these reasons led to a slight reduction in the thresholds for all products.

The first part of the analysis that was devoted to all but the western and northern directions, pointed to a relatively high accuracy (around 80-90%) of radar measurement of convective precipitation depending on the configuration of the threshold values of the SUM MERGE combined product. The threshold limits of radar products corresponded to coefficients 1 and 2; however, the measurement results were underestimated by 4 dBZ (VIL about 2.5 kg/m^2) against a coefficient of 3. This was mainly due to the different properties of the measured local and areal convective precipitation.

The second part of the evaluation was aimed on the threshold limits only for western and northern directions with analogous development trend as in the first part. The only difference was, that the average measured values of precipitation were slightly lower than the threshold limits especially for coefficients 2 and 3. This was mainly due to differences in the type of convective clouds, where in the first result part, the convective precipitation occurring in warmer unstable air mass usually had a higher intensity compared to that for western and northern directions only. This fact naturally implies increase of the risk of flash floods.

For both subdivision of the flow directions, the lowest measured values were achieved for the ETOP product in terms of accuracy in the order of 20 to 30% lower than for the CAPPI and VIL products. Therefore, this product will not be evaluated by the conversion algorithm, due to possible distortion of the output data, especially for local convective precipitation.

Future research will focus on continuing to evaluate the accuracy of measurement of radar products in other historical situations in order to achieve maximum accuracy of input data conversion and computation of statistical and nowcasting forecast of convective precipitation. The outputs will be used for the planning and implementation of flood prevention measures within the crisis management of the region and their municipalities with extended powers.

ACKNOWLEDGMENT

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