J. Hydrol. Hydromech., 71, 2023, 1, 111–122
https://doi.org/10.2478/johh-2022-0037
©2023 Patrik Sleziak et al., published by Sciendo. This work is licensed under the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International Licence.

sciendo Journal of Hydrology and Hydromechanics Institute of Hydrology SAS

Accuracy of radar-estimated precipitation in a mountain catchment in Slovakia

Patrik Sleziak[1*], Martin Jančo[1], Michal Danko[1], Ladislav Méri[2, 3], Ladislav Holko[1]

[1] Institute of Hydrology, Slovak Academy of Sciences, Dúbravská cesta 9, 841 04 Bratislava, Slovakia.
[2] Slovak Hydrometeorological Institute, Jeséniova 17, 833 15 Bratislava, Slovakia.
[3] Department of Astronomy, Physics of the Earth, and Meteorology, Comenius University in Bratislava, Mlynská dolina 842 48, Bratislava 4, Slovakia.
[*] Corresponding author. E-mail: sleziak@uh.savba.sk

Abstract: Accurate estimation of precipitation in mountain catchments is challenging due to its high spatial variability and lack of measured ground data. Weather radar can help to provide precipitation estimates in such conditions. This study investigates the differences between measured and radar-estimated daily precipitation in the mountain catchment of the Jalovecký Creek (area 22 km^2, 6 rain gauges at altitudes 815–1900 m a.s.l.) in years 2017–2020. Despite good correlations between measured and radar-based precipitation at individual sites (correlation coefficients 0.68–0.90), the radar-estimated precipitation was mostly substantially smaller than measured precipitation. The underestimation was smaller at lower altitude (on average by –4% to –17% at 815 m a.s.l.) than at higher altitudes (–35% to –59% at 1400–1900 m a.s.l.). Unlike measured data, the radar-estimated precipitation did not show the differences in precipitation amounts at lower and higher altitudes (altitudinal differences). The differences between the measured and radar-estimated precipitation were not related to synoptic weather situations. The obtained results can be useful in preparation of more accurate precipitation estimates for the small mountain catchments.

Keywords: Radar-estimated precipitation; Precipitation estimates; Daily precipitation; Synoptic weather situations.

INTRODUCTION

Hydrological cycle in the mountain environment has some specific features. The distribution of basic climatic elements (atmospheric precipitation and air temperature) and vegetation is significantly affected by large altitudinal differences. Windward and leeward effects during precipitation, movement of snow from the ridges to the feet of slopes and into the valleys and the influence of terrain configuration are typical phenomena found in mountains. Small mountain catchments in the highest mountains of Slovakia are often forested, their average elevation exceeds 1000 m a.s.l., the slopes are steep (e.g. the average slope of about 30° as in the catchments of the Tatra Mountains) and they have shallow soils (depth around 1 meter) and small riparian areas (Holko et al., 2011).

Precipitation is one of the basic elements of the water balance and the most important input in catchment hydrological modelling. It is measured by rain gauges at selected sites (points). Due to the extreme natural conditions (i.e. complex topography and highly elevated regions), mountain catchments are less populated and therefore sparsely covered by measurement networks. Precipitation stations are often situated in the lower parts of the catchments. This might pose a problem especially in small mountain catchments, because due to positive elevation gradients in precipitation, catchment areal precipitation can be underestimated. The radar-based precipitation products provide a potential source of useful data on precipitation in larger regions (Fairman et al., 2015). They could potentially be useful also in small mountain catchments. However, they are affected by various uncertainties. For instance, the radar signal over high elevated areas may be affected by beam blockages, vertical reflectivity profiles, fluctuation in atmospheric conditions, etc. (McKee and Binns, 2016; Villarini and Krajewski, 2010).

A number of studies illustrated the potential of the radar-based precipitation products for hydrological applications (e.g., Abon el al., 2016; Berne et al., 2005; Espinosa et al., 2015; Gilewski and Nawalany, 2018; Hazenberg et al., 2011). For example, Abon el al. (2016) tested the added value of radar-based rainfall estimates for streamflow simulations in the Marikina River Basin (the Philippines). They showed that for their study site, the radar-based product performed similarly as the measured rainfall data. Berne et al. (2005) tested the potential of weather radar in southern Ardennes, France. Their results showed biases of the radar estimates with respect to gauge estimates between +128% and −42% for six precipitation events. Espinosa et al. (2015) compared three Doppler radar datasets against rain gauge measurements for two storm events in a desert area of Southern California, USA. Their results pointed out that topographic interference with the radar outcomes can be a significant factor leading to major differences between the radar and rain gauge data. Germann et al. (2006) presented radar algorithm improvements for better radar precipitation estimates over Switzerland. They showed that modifications in the algorithms of the operational QPE (Quantitative Precipitation Estimate) product has resulted in reduction of bias/scatter. The improvement in scatter was mainly achieved by the meso-beta profile and the local bias correction. Fairman et al. (2015) showed that the radar precipitation product provided a useful depiction of the annual distribution of precipitation across the Great Britain and Ireland. Gilewski and Nawalany (2018) compared the performance of three different precipitation data sources (rain gauge, radar and satellite precipitation estimates) for event-based hydrologic modelling in a small mountainous catchment (the Upper Skawa catchment) in Poland. They concluded that radar and satellite precipitation estimates were suitable for the event-based modelling. Hazenberg et al. (2011) showed that for the hilly region of

the Belgian Ardennes, the radar product underestimated the amount of precipitation as compared to the rain gauges. Kreklow et al. (2020) evaluated two radar products (RADOLAN and RADKLIM) against the rain gauge data (annual/seasonal/hourly) for the territory of Germany. Both radar products tended to underestimate total precipitation amounts and high intensity rainfalls. Schleiss et al. (2020) tested the accuracy of six different radar products in four countries (Denmark, Finland, the Netherlands and Sweden) with the emphasis on quantification of discrepancies between the radar precipitation estimate and measured precipitation during heavy precipitation. They showed that although the overall agreement in heavy precipitation was good (correlation coefficient 0.7–0.9), all six radar products exhibited a clear pattern of underestimation compared with rain gauges. Hofstätter et al. (2018) evaluated the variability of heavy precipitation over central Europe with respect to cyclone track types. High frequency of strong cyclones was found to be the key factor in explaining the seasonality of heavy precipitation.

While some studies reported underestimation of measured precipitation (e.g., Goudenhoofdt and Delobbe, 2016; Hazenberg et al., 2011; Kreklow et al., 2020; Schleiss et al., 2020; Smith et al., 2012) other showed its overestimation (e.g., Fairman et al., 2015; Marra and Morin, 2015). Despite the existence of numerous studies, the results are difficult to compare due to different regions, physiographic conditions, differences in radar hardware, correction algorithms, etc. Comparative studies in other regions are therefore still needed. Hydrological Forecasting Service (HFS) of Slovak Hydrometeorological Institute recently drew attention to the problem of acceptable flood forecasting in mountains, related to the accuracy of precipitation estimates. They could not forecast recent big rainfall-runoff event (18 July 2018) in the mountainous Jalovecký Creek catchment with required accuracy (Hrušková and Hlaváčiková, 2022). A more detailed analysis showed that precipitation input data derived by the radar were significantly underestimated; the radar-based precipitation estimate was approximately 40 mm while measured precipitation was around 140 mm. Therefore, a more detailed analysis could be useful to improve the radar-based estimates.

This study evaluated a new radar product developed for the territory of Slovakia. Comparison of the differences between the radar-estimated and measured precipitation at different elevations in a small mountain catchment in northern Slovakia (the Jalovecký Creek catchment) was supplemented by the analysis of the differences during different synoptic weather situations. The objectives of the study are a) to evaluate the differences between measured precipitation and the newly developed radar-estimated daily precipitation product at different elevations, b) examine if the differences depend on the synoptic weather situation and c) quantify the differences for greater precipitation amounts that can cause flood situations.

MATERIALS AND METHODS

Study area and data

The study was conducted in the mountain catchment of the Jalovecký Creek located in the Western Tatra Mountains (Fig. 1). The catchment features high altitudinal differences (815 to 2178 m a.s.l.) in a small area (22.2 km^2). Hydrological research aimed at the improvement of knowledge on hydrological cycle of the highest part of the Western Carpathians is conducted there

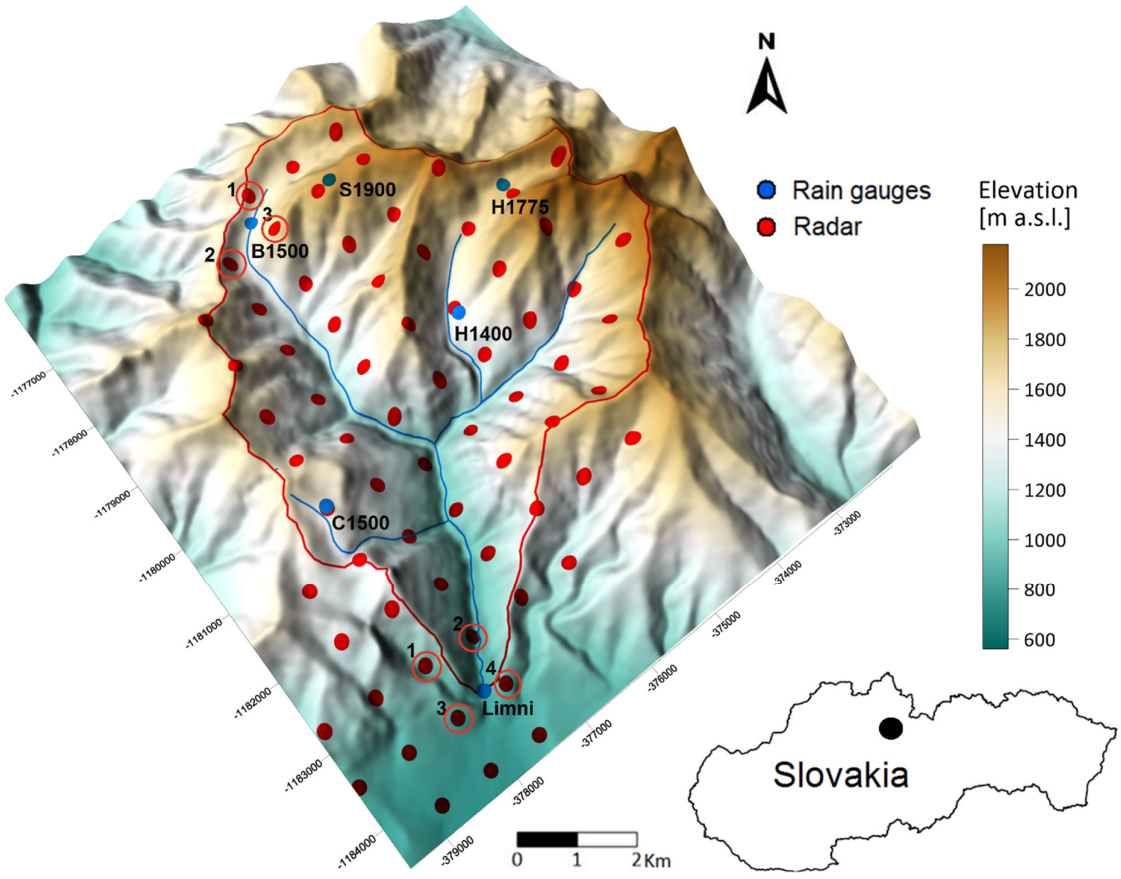

Fig. 1. Precipitation measurement network (the blue points) and the nodes of radar images (the red points); the circled points indicate nodes that were used for computation of averages for sites Limni and B1500.

since the end of the 1980s (e.g. Holko et al., 2021). Precipitation measurement network built in the catchment is denser than in other small mountain catchments of Slovakia and provides data for hydrological modelling (Danko et al., 2015a, b) or investigation of precipitation spatial and temporal variability (e.g. Holko et al., 2014).

The study is based on daily precipitation data measured at six sites in years 2017–2020. The sites were selected to cover different altitudes, ranging from 815 to 1900 m a.s.l. (Fig. 1). Precipitation stations C1500 (1500 m a.s.l.) and Limni (815 m a.s.l.) provided daily precipitation for the entire year measured by the weighing gauge TRwS 504. Tipping bucket rain gauges (Pronamic Pro) provided the spatially distributed precipitation data at other four sites H1400 (1400 m a.s.l.), B1500 (1500 m a.s.l.), H1775 (1775 m a.s.l.) and S1900 (1900 m a.s.l.) in summer months (June to September).

Radar-based precipitation estimates

The radar-based precipitation product used in our study was derived from the network of four C-band, dual-polarized Selex-Gematronik Meteor 735 CDP10 weather radars of the Slovak Hydrometeorological Institute and computed by the qRad and qPrec software packages developed at the Slovak Hydrometeorological Institute (Méri et al., 2021). The qRad software estimates the actual quality of the radar volume data by various quality indices and corrects some undesirable effects on the measurement (e.g., beam-blockage, ground-clutter, non-meteorological echoes). The qPrec package uses the probabilistic approach to estimate the rainfall intensity based on heterogeneous input data (rain gauges, radars, satellites). The nodes from a regular grid (spatial resolution of 1x1 km identical to the resolution of the qPrec product) covering the Jalovecký Creek catchment were used in the study. Separate calibration functions to convert reflectivity values to rainfall probability and rainfall rate are derived for each radar according to the latest rain-gauge measurements. The aim of the calibration functions is to reduce the systematic bias in the radar-based precipitation estimate taking into account also the seasonal changes. Only one calibration function per radar is computed and represents the average for the entire area covered by the given radar. This can lead to over – or under estimation in some sub-areas of the domain. The calibrated input data fields are combined according to their precision and actual quality (Méri et al., 2021). The main limiting factors of radar measurements in mountainous areas are the beam-blockage and ground clutter with its possible removal from the reflectivity values by the radar software. These effects can be depicted by the minimal detectable height map for the used network shown in Fig. 2. The yellow and greenish areas in the Figure represent radar beam near the ground level where precipitation estimation can be done more precisely. However, these areas are also more influenced by the ground clutter (high reflectivity values due to radar beams hitting the surface). The blue and purple areas in Fig. 2 indicate that radar beams are higher above the ground level due to the blockage of the lower beams. The reflectivity values detected in these areas represent a higher level of the atmosphere and are less correlated with the rainfall intensities on the ground.

The evaluation of radar-based precipitation estimates was based on the comparison with measured precipitation. Radar data from the nodes close to rain gauges C1500, S1900, H1775 and H1400 were directly used in the comparison. Averages of the radar-based precipitation estimates from four and three surrounding nodes were used for rain gauges Limni and B1500, respectively (Fig. 1). The agreement between the two precipitation datasets was examined by the bias expressed in per cents (Equation (1) below) and in millimeters (Equation (2)). Pearson correlation coefficients between measured and radar-based precipitation and visual examination were used as well.

$$\Delta P_{\%} = \left(\frac{P_{radar} - P_{measured}}{P_{measured}} \right) * 100 \quad (1)$$

$$\Delta P_{mm} = P_{radar} - P_{measured} \quad (2)$$

The differences between the radar-estimated and measured precipitation were evaluated also with account of the synoptic weather situations that occurred on particular days. The aim was to find out how are the differences related to particular synoptic situation. Synoptic weather situation for each day of the study period was obtained from the Slovak Hydrometeorological Institute (SHMI, 2021). At present, a common typing of synoptic weather situations is used in Slovakia and in the Czech Republic. The typing is based on the catalogue of Hess and Brezowsky (1997), Brádka et al. (1961) and Ballon et al. (1964). It contains 28 types (Table 1) characterized by the direction of the air masses flow or its typical short-term changes, regime of the pressure field, the way the front passes and the influx or alternation of air masses having certain origin (SHMI, 2021).

Table 1. Synoptic weather situations.

Synoptic situations	Abbreviation
trough over central Europe	B
travelling trough	Bp
cyclone over central Europe	C
upper cyclone	Cv
east cyclonic	Ec
north cyclonic	Nc
north-east cyclonic	NEc
north-west cyclonic	NWc
south-east cyclonic	SEc
south-west cyclonic of the 1st type	SWc1
south-west cyclonic of the 2nd type	SWc2
south-west cyclonic of the 3rd type	SWc3
west cyclonic	Wc
west cyclonic with southern pathway	Wcs
entry of the frontal zone	Vfz
anticyclone over central Europe	A
travelling anticyclone of the 1st type	Ap1
travelling anticyclone of the 2nd type	Ap2
travelling anticyclone of the 3rd type	Ap3
travelling anticyclone of the 4th type	Ap4
east anticyclonic	Ea
north-east anticyclonic	NEa
north-west anticyclonic	NWa
south anticyclonic	Sa
south-east anticyclonic	SEa
south-west anticyclonic	SWa
west anticyclonic	Wa
west anticyclonic of summer type	Wal

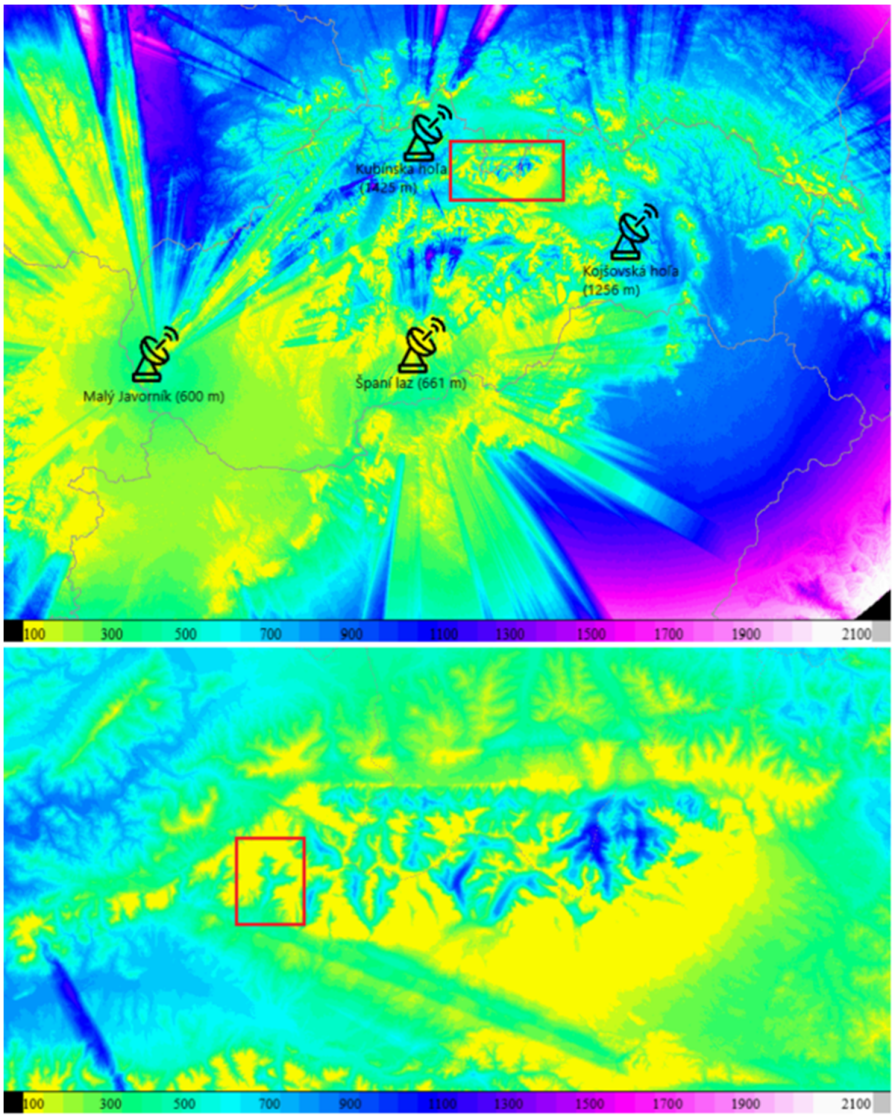

Fig. 2. Location of the radars used in this study, heights of the antennas above the sea level and minimal detectable height above the ground [m]; the red rectangle in the upper panel indicates the Tatra Mountains region that is shown in a greater detail in the lower panel; study area is indicated in the lower panel by the red triangle.

RESULTS

Characteristics of measured precipitation and catchment runoff

Precipitation occurred in the catchment quite often, i.e. in 48% to 60% of days in the study period (Table 2). Daily precipitation rarely exceeded 100 mm even at higher altitudes (1–2 times at different sites in the study period) and it was most frequently in the interval 0.1 mm to 5 mm (in 42% to 61% of days with precipitation). The difference in daily precipitation between the lower and higher altitudes becomes visible for greater precipitation amounts – while days with precipitation of up to 20 mm represented 95% of all days with precipitation at 820 m a.s.l. (site Limni), at higher altitudes they represented only 93% (less in the warm period of the year).

Precipitation occurred most frequently in days with synoptic weather situations B, Bp, NEc, NWc and Wc (12%, 11%, 9% and 9% of all days with precipitation at C1500, respectively). B and Bp are synoptic situations characterized by trough of the low air pressure above or passing through the Central Europe, respectively. NEc, NWc and Wc are cyclonal situations (north-eastern, north-western and western). In the warm part of the year (June to September), precipitation occurred most frequently during synoptic weather situations B, Bp, and NEc (16%, 18% and 14% of days with precipitation at C1500, respectively). The same synoptic weather situations were the most important also from the point of view of precipitation amounts (Fig. 3). The wettest one was the NEc that brought about 20% of annual precipitation (25%–29% of precipitation in period June to September).

The radar-based precipitation estimation is especially important for flood forecasting, i.e. for the high flows caused either by short, very intensive precipitation or long wet periods. Fig. 4 shows daily measured catchment (areal) precipitation and runoff in the warm period of years 2017 to 2020 and the relationship between the peakflow and daily precipitation

Table 2. Total number of days in the study period, number of days with precipitation and frequencies of days with daily precipitation in intervals 0.1–5.0 mm (1*), 5.01–10 mm (2*), 10.01–15.0 mm (3*) and 15.01–20 mm (4*). Values on the top/bottom characterize measured/radar-based precipitation, respectively.

Period	Site	Total number of days	Days with precipitation (0.1 mm and more) [%]	1* [%]	2* [%]	3* [%]	4* [%]	Σ 1*–4* [%]
January to December	**Limni**	1553	53	66	19	7	3	95
			52	66	19	9	2	96
	C1500	1553	66	62	17	9	5	93
			51	68	17	9	2	96
June to September	**Limni**	488	49	56	20	11	6	93
			50	58	21	11	3	93
	C1500	488	58	54	17	10	7	88
			51	57	19	13	5	94
	H1400	488	58	45	16	12	7	80
			51	58	19	11	4	92
	B1500	488	58	47	19	12	5	83
			52	59	18	10	6	93
	H1775	488	57	42	19	11	8	80
			53	58	21	10	3	92
	S1900	488	60	48	17	11	8	84
			53	58	19	10	6	93

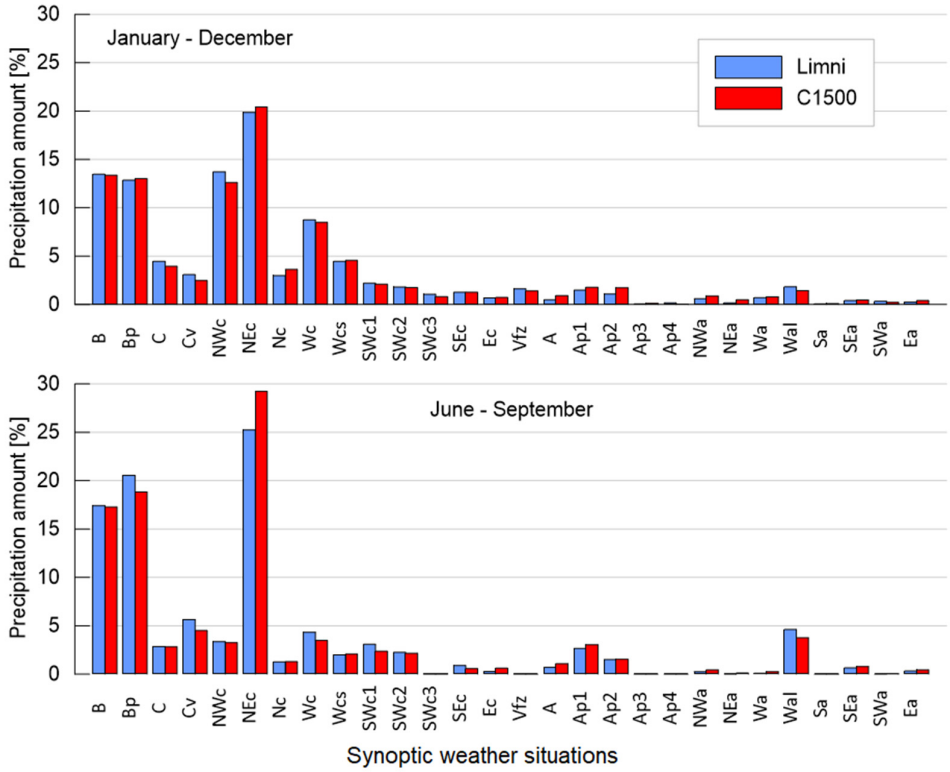

Fig. 3. Contribution of measured precipitation during different synoptic weather situations to total annual precipitation amount (January–December) and to total precipitation in the warm period of the year (June–September).

during selected events with high peakflow. Except for 2019, greater response of catchment runoff to precipitation occurred only 1–2 times in the warm periods of years 2017–2020. Although some events were caused by wet periods longer than one day, daily peakflow from the Jalovecký Creek catchment was well correlated with daily precipitation (coefficient of determination 0.89) that highlights the importance of correct estimation of the short-term high precipitation events. The cold period of the year (i. e. October to May) was excluded from the evaluation to avoid the uncertainties in the rainfall-runoff relations caused by the snow cover formation and melt.

Comparison of measured and radar-estimated precipitation

The differences between measured and radar-estimated precipitation summarized over longer periods (entire years, warm periods of the years) are given in Table 3. The radar-estimated precipitation was smaller than measured precipitation. The underestimation for the stations located in mountains and at higher altitudes (1400–1900 m a.s.l.) was substantially greater (between –35% and –59%) than for the station located at the lowest elevation (815 m a.s.l.) near catchment outlet (between –4% and –17%).

Table 3. Average bias values (in % – the value on the top, in mm – the value below it) at different elevations in the entire year (January–December) and in its warm period (June–September); the bias was calculated for precipitation totals over particular periods; minus signs (–) indicate that the radar-based precipitation underestimated the observed precipitation.

Period	Site	2017	2018	2019	2020
January to December	**Limni**	11 111	–7 –54	–7 –73	–23 –285
	C1500	–38 –644	–40 –519	–31 –436	–45 –747
June to September	**Limni**	–4 –25	–11 –52	–9 –35	–17 –113
	C1500	–35 –316	–39 –293	–35 –185	–37 –331
	H1400	–59 –761	–56 –590	–49 –338	–56 –661
	B1500	–46 –457	–43 –367	–40 –243	–51 –530
	H1775	–54 –673	–52 –544	–53 –407	–55 –669
	S1900	–50 –528	–52 –529	–53 –293	–55 –527

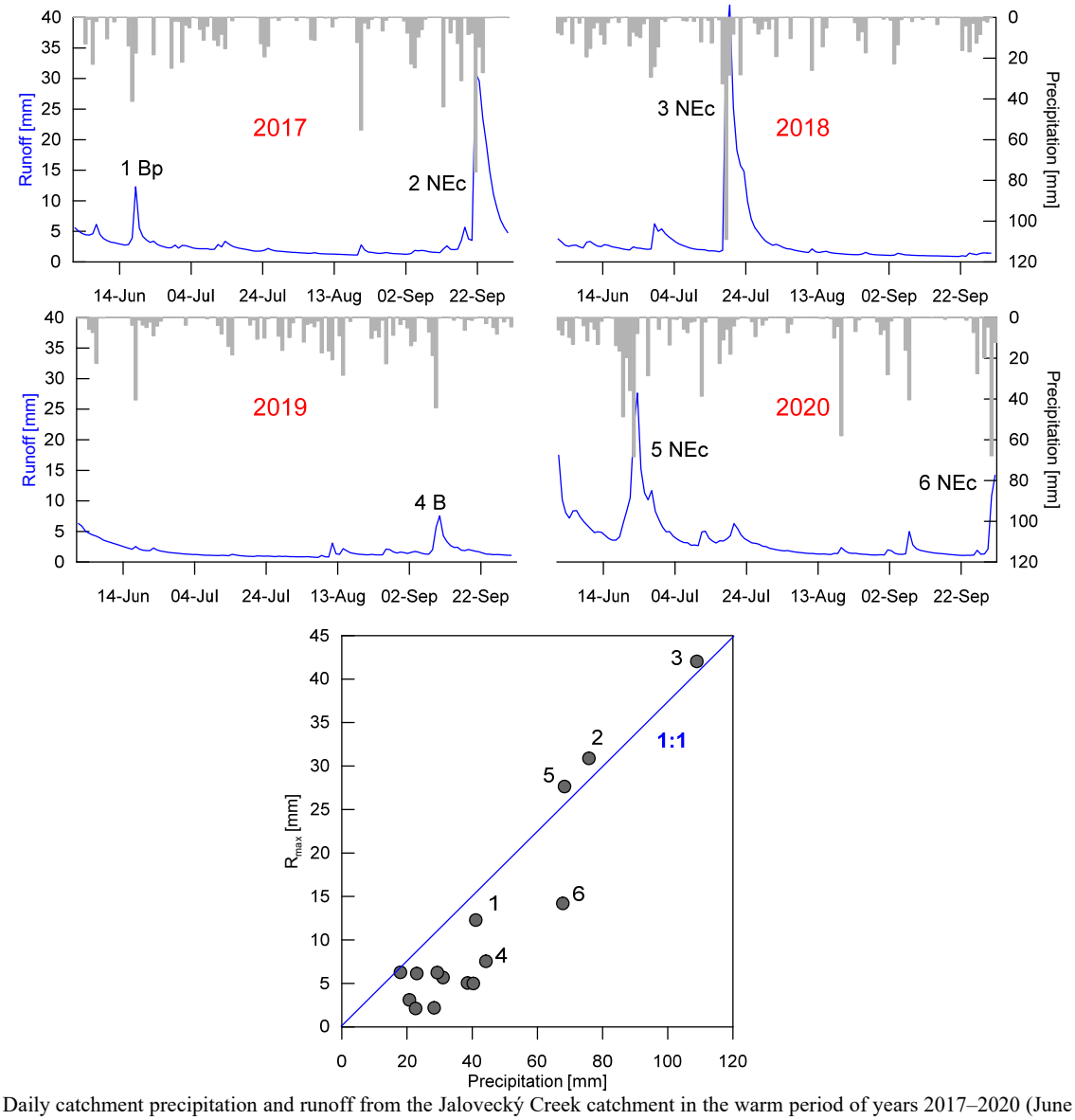

Fig. 4. Daily catchment precipitation and runoff from the Jalovecký Creek catchment in the warm period of years 2017–2020 (June to September) and the relationship between the event peakflow and daily precipitation on the same day or on the day preceding the peakflow; the numbers denote selected greatest runoff events in individual years and synoptic weather situations during which they occurred.

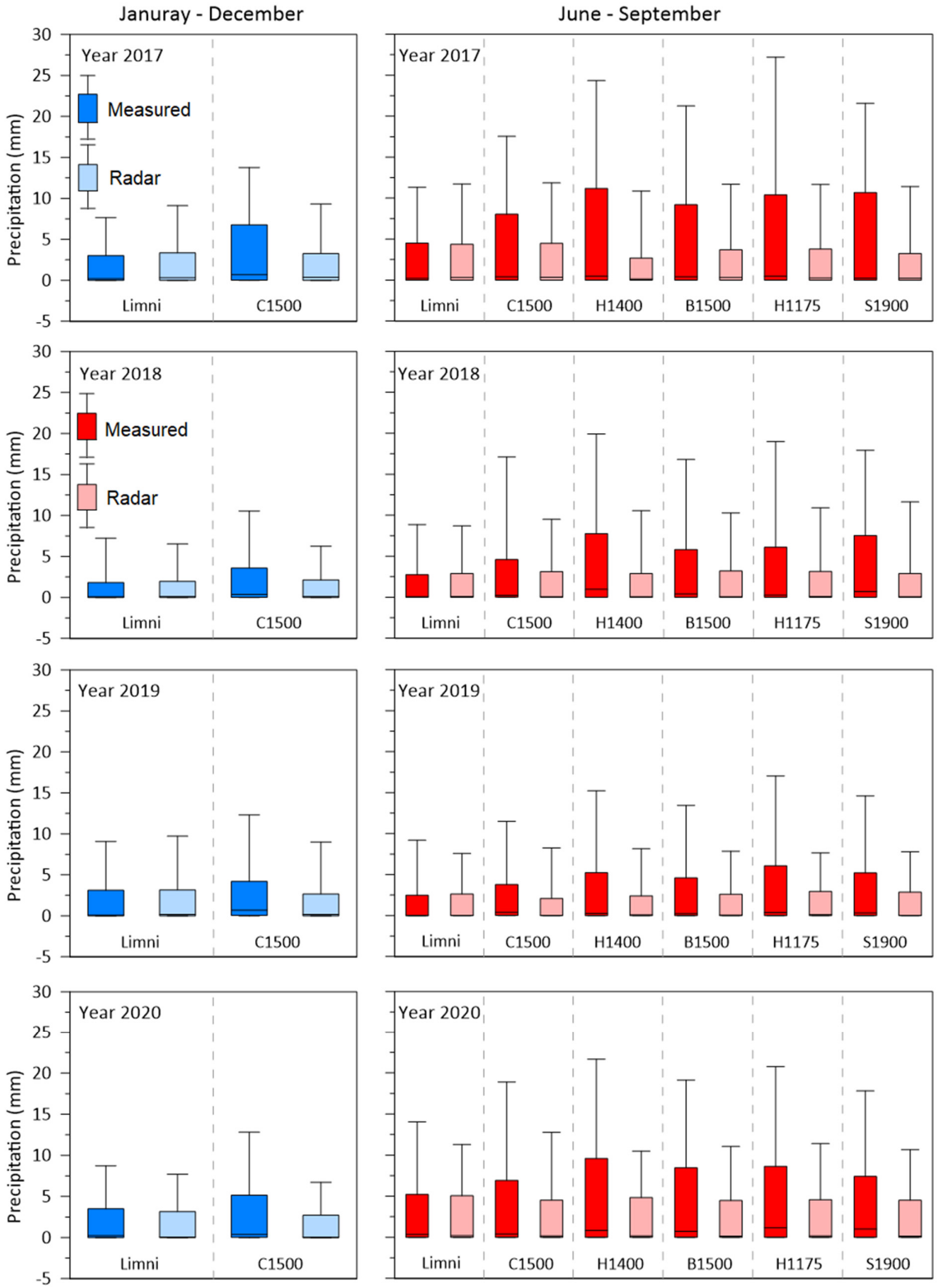

Fig. 5. Boxplots of measured and radar-estimated daily precipitation; the whiskers represent percentiles 10 and 90, the boxes are the upper and lower quartiles and the center line shows medians.

Fig. 5. indicates that except the lowest altitude (Limni), underestimation of the radar-based daily precipitation was systematic (smaller upper quartiles and maxima compared to measured data).

Systematic underestimation is confirmed by Fig. 6 showing daily scatterplots of measured against radar-based precipitation. The underestimation was especially significant for the high

measured precipitation amounts which are important for flood formation.

The Pearson correlation coefficients (Fig. 7) between measured and radar-estimated precipitation varied between 0.68 and 0.90. Except site H1400 they varied quite a lot between the years. The differences between the correlations calculated for the entire years and their warm periods were small, especially for the year of 2017 at site Limni.

Comparison of measured and radar-based daily precipitation during selected runoff events with the greatest peakflow in the warm periods of years 2017–2020 (Fig. 4) shown in Fig. 8 confirms substantial underestimation of the radar-based precipitation except for event 4 which had the smallest peakflow of all selected events. Fig. 8 also shows that while measured data mostly documented a big difference in precipitation amounts between the lowest-elevation and the higher-elevation stations, the radar-based data do not reveal such a pattern. This is also shown in Fig. 9 showing measured and radar-estimated summer precipitation totals (June to September) at different altitudes. The differences in precipitation amounts in different warm seasons are much less visible in the radar-based precipitation as well.

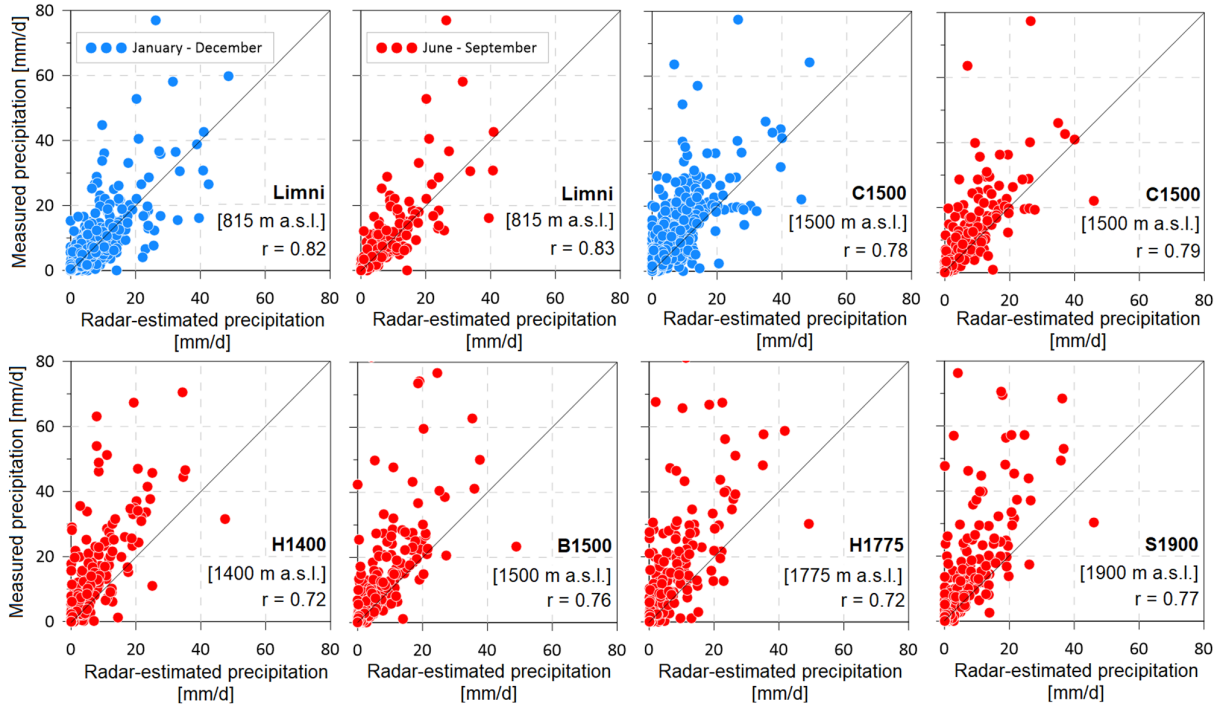

Fig. 6. Measured versus radar-estimated daily precipitation at different elevations in the entire year (January–December) and its warm period (June–September) in the study period 2017–2020; the diagonal represents the 1:1 line.

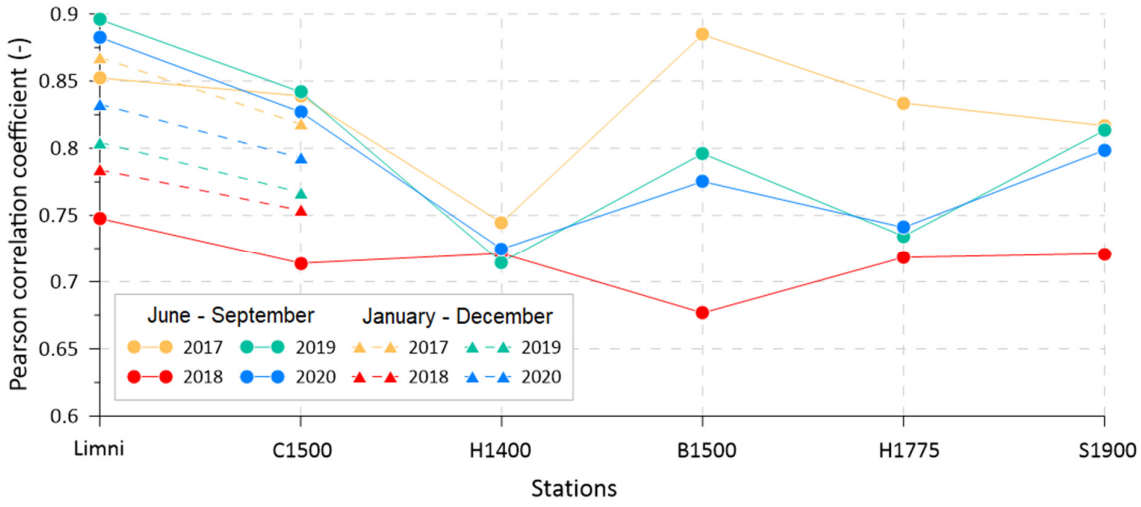

Fig. 7. Correlations between measured and radar-based precipitation at six stations in the entire years and in their warm periods.

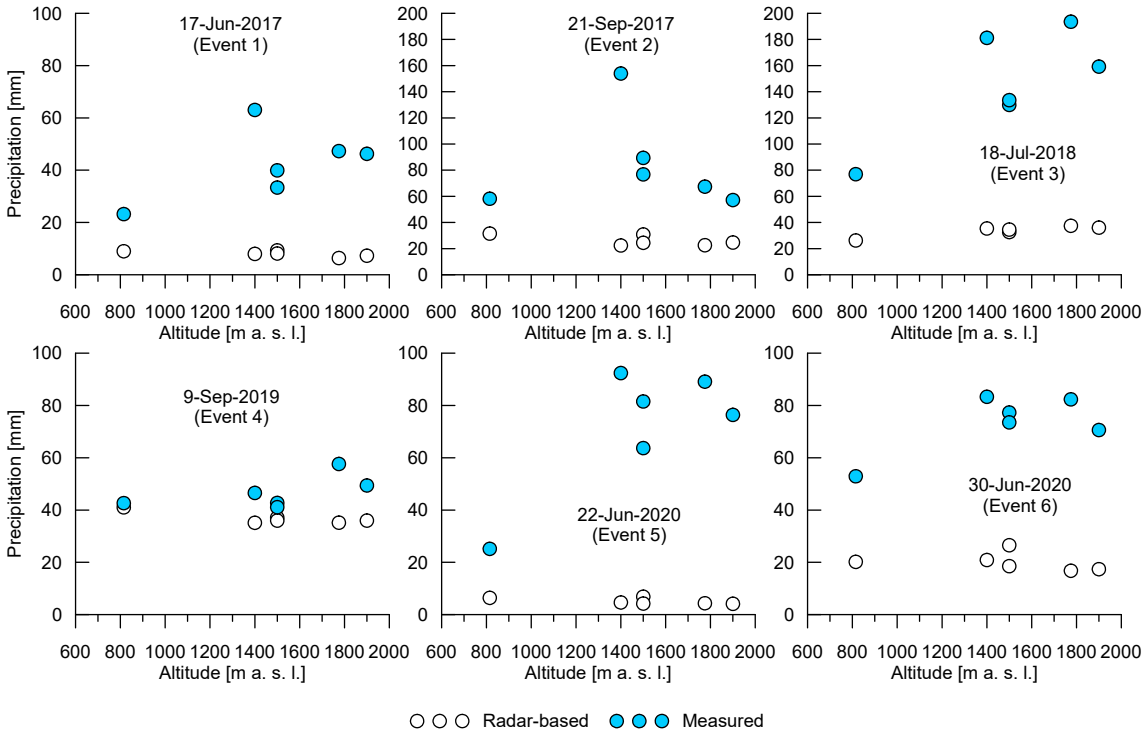

Fig. 8. Measured and radar-estimated daily precipitation at different altitudes for the selected greatest runoff events (the events are shown in Fig. 4).

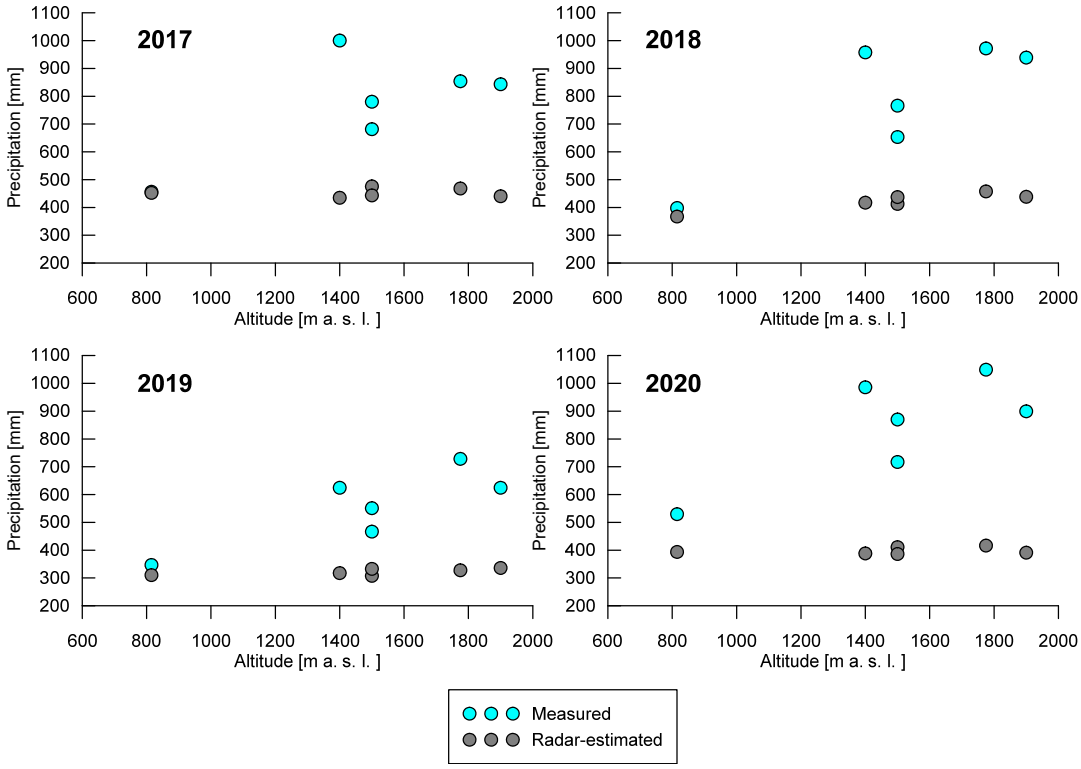

Fig. 9. Measured and radar-estimated total summer precipitation (June to September) at different altitudes; the two numbers are almost the same at the altitude of 800 m a.s.l. in summer 2017.

The bias of the radar-estimated precipitation did not show clear relationships with the synoptic weather situations (Figs. 10 and 11). It was often substantial for all weather situation, but the underestimation of the radar-based precipitation for synoptic weather situations NEc and NWc was greater than for B and Bp. The radar-based precipitation for the site Limni was mostly

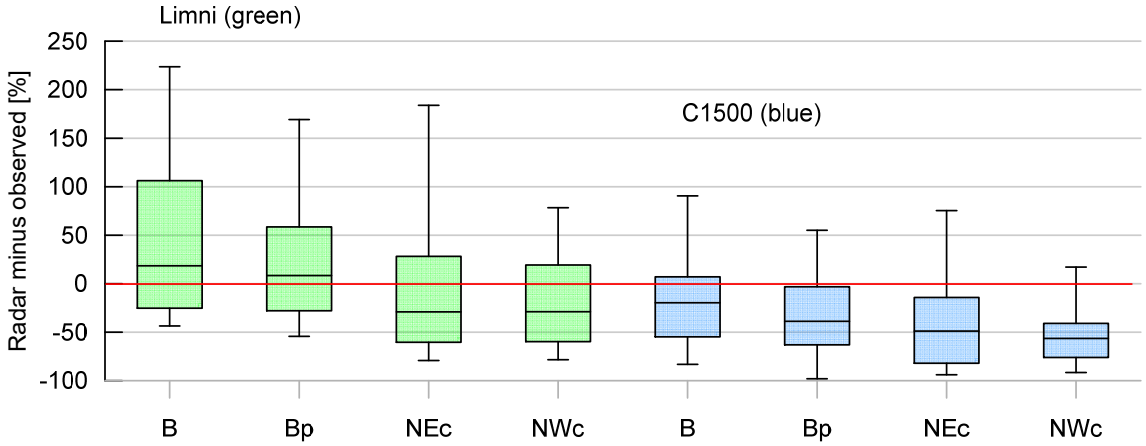

Fig. 10. Comparison of radar-estimated and measured daily precipitation for sites Limni and C1500 in the entire year (January–December) for the synoptic weather situations that were most frequently accompanied by precipitation; the whiskers represent percentiles 10 and 90, the boxes are the upper and lower quartiles and the center line shows medians; the number of values for individual boxplots varies between 86 and 113.

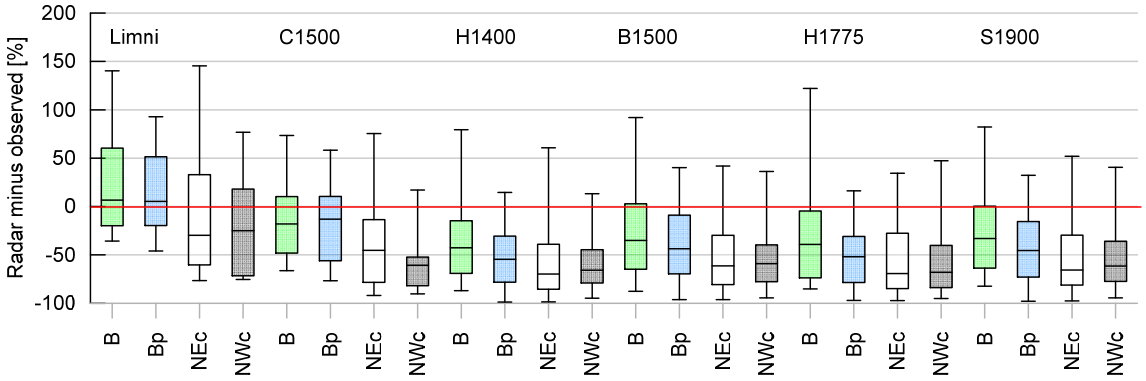

Fig. 11. Comparison of radar-estimated and measured daily precipitation for all stations for the warm period of the year (June–September) for synoptic weather situations that were most frequently accompanied by precipitation; the whiskers represent percentiles 10 and 90, the boxes are the upper and lower quartiles and the center line shows medians; the number of values for individual boxplots vary between 10 and 115.

greater than measured precipitation during synoptic weather situations B and Bp. For other situations and sites it was mostly lower than measured precipitation. Median bias between measured and radar-estimated precipitation during the NEc weather situation (i.e. the one bringing the highest precipitation amounts) in the warm period of the year (when the floods usually occur), were mostly greater than –50% (except for station Limni).

DISCUSSION

Our results show that the weather radar precipitation product mostly substantially underestimated measured precipitation in the studied mountain catchment. This conclusion is consistent with several studies evaluating the accuracy of various radar-based precipitation products (e.g., Goudenhoofdt and Delobbe, 2016; Hazenberg et al., 2011; Kreklow et al., 2020; Schleiss et al., 2020; Smith et al., 2012). The underestimation of measured precipitation was more significant for higher elevations. This may be related to radar coverage/signal that is limited due to terrain complexity and the shading problem. As it was pointed out by Berne et al. (2005), interception of the radar beam in mountainous areas by surrounding terrain is generally a major concern of the accuracy of radar-based precipitation products. Other sources of errors that affect the weather radar quality can be related to distance from the radar site, hardware, correction algorithms, etc. (e.g. McKee and Binns, 2016; Sokol et al., 2021). Underestimation of measured precipitation found in our study area is in general agreement with the results presented e.g. by Schleiss et al. (2020) or Kreklow et al. (2020).

High values of the correlation coefficients (the correlations explained 82% to 95% of variability) suggest that although the radar-based precipitation was underestimated compared to measured precipitation, the underestimation at individual sites was relatively stable.

Examination of the radar-based precipitation estimates for the six greatest runoff events in individual years (June to September) showed that the radar-estimated precipitation did not reproduce the observed altitudinal pattern of precipitation (much greater precipitation amounts at higher altitudes). Precipitation during five of the six events were significantly underestimated by the radar (except the event that occurred in September 2019). This may be caused by the fact that the calibration algorithm employs measured precipitation data for each radar from radius of about 240 km. This radius is probably often too high for the correct estimation of precipitation in mountains, because it covers large areas where precipitation is much smaller than in mountains.

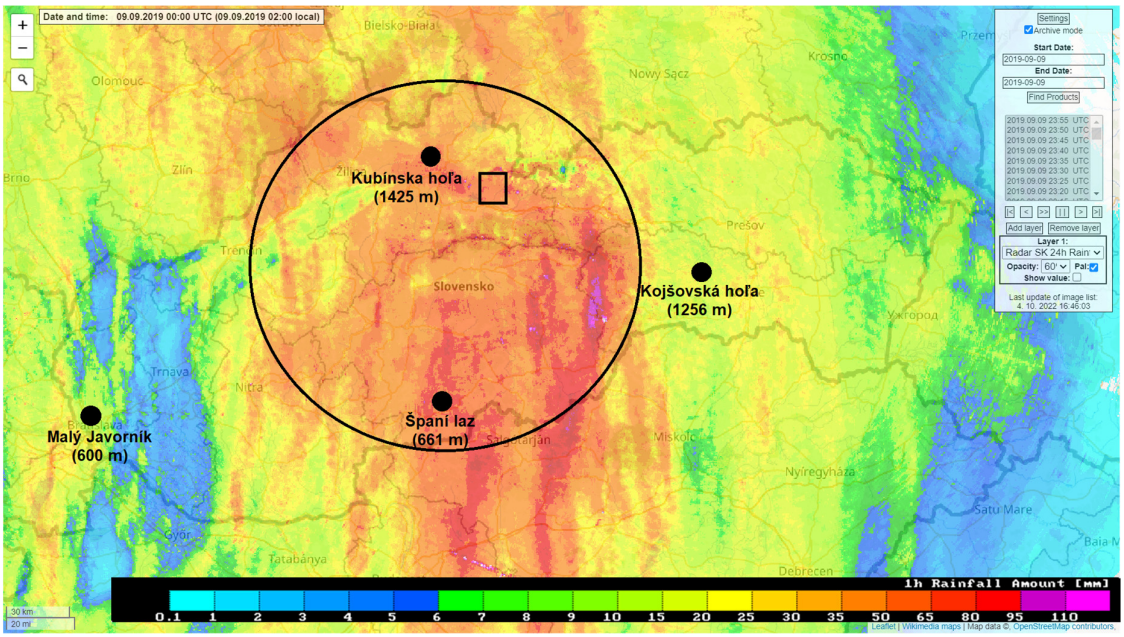

Fig. 12. 24-hour radar-estimated precipitation on 9, September 2019; the study area is indicated by a rectangle.

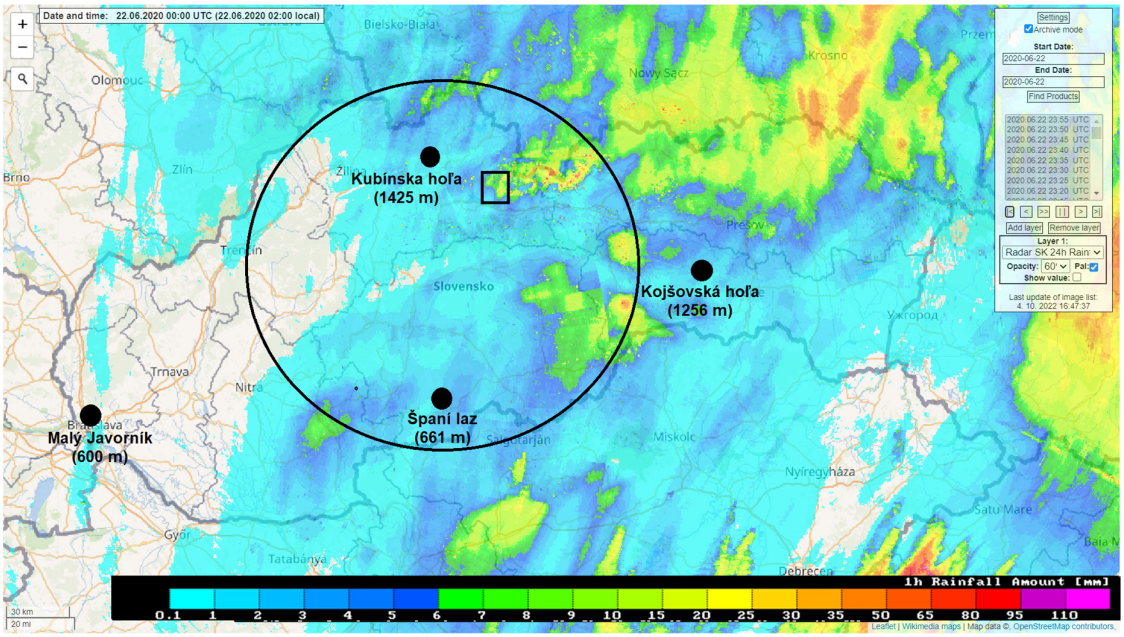

Fig. 13. 24-hour radar-estimated precipitation on 22, June 2020; the study area is indicated by a rectangle.

Thus, the radar-based precipitation estimates would be biased towards smaller precipitation amounts. This could be confirmed by Fig. 12 showing the situation around the radar at Kubínska hoľa that has the highest weight for precipitation estimates in the study area. It shows that on 9 September 2019, when the radar-based precipitation estimates were most similar to measured precipitation, a large territory surrounding the radar had high amounts of precipitation, i.e. the spatial differences in precipitation were less significant. Spatial differences in precipitation during other selected events (e.g. on 22 June 2020, Fig. 13), were greater, and thus the resulting calibration function also produced greater bias.

Similarly to precipitation during selected events, total summer radar-based precipitation failed to reproduce the elevation gradient found in measured data. It can thus be concluded that the radar-based precipitation could not provide correct input data for the event-based hydrological modelling in the studied mountain catchment (e.g. runoff forecasting, simulation of spatial distribution of soil moisture, runoff generation, etc.). This result does not agree with that of Gilewski and Nawalany (2018) who also studied a small mountainous catchment located on the northern part of the Carpathian Mountains. However, unlike our study catchment, the catchment of the Upper Skawa river is much larger (240.4 km^2) and had smaller mean altitude. Gilewski and Nawalany (2018) also used different precipitation product than the one that was used in our study.

Our study extends previous assessments by the analysis of the differences between the radar-estimated and measured precipitation taking into account synoptic weather situations. The

differences for trough situations B and Bp were smaller than for the cyclonal situations NEc and NWc (Fig. 11). However, it was not possible to conclude that the radar-estimated precipitation estimates are acceptably accurate for a particular synoptic weather situation or part of the year (summer versus the entire year).

CONCLUSIONS

We have compared the radar-estimated and measured precipitation in a small mountain catchment to assess the potential using the earlier for hydrological simulations. The results indicated major challenges in the radar-based precipitation estimation over complex topography. The weather radar consistently and significantly underestimated the measured precipitation and did not correctly reflect the differences in precipitation amounts at low and high altitudes.

The underestimation of measured precipitation was probably caused by local deviations from the average calibration curves per radar used by the qPrec software. More localized or altitude-based bias-correction of the radar precipitation estimates combined with installation of more rain gauges in mountains could help to solve the detected problems. Reduction of the effects caused by the topography by means of a gap-filling x-band radar can be considered as well. In the future, it would also be useful to fix the radar-estimated precipitation with a correction function that includes the altitude. Hourly precipitation estimates from the modified radar product that are more important for the correct flood forecasting can be tested in the future if the daily estimates will better compare to measured precipitation.

Acknowledgements. This study was supported by the grants from the Slovak Academy of Sciences (project VEGA No. 2/0065/19) and from the Slovak Research and Development Agency (project APVV No. 19-0340). Financial support by the Stefan Schwarz grant of the Slovak Academy of Sciences is also gratefully acknowledged.

REFERENCES

Abon, C.C., Kneis, D., Crisologo, I., Bronstert, A., David, C.P.C., Heistermann, M., 2016. Evaluating the potential of radar-based rainfall estimates for streamflow and flood simulations in the Philippines. Geomat. Nat. Hazards Risk, 7, 1390–1405.

Ballon, L., Forgáč, P., Molnár, F., 1964. Weather over the territory of Slovakia in typical weather situations. Hydrometeorologický ústav, Prague, 30 p. (In Slovak.)

Berne, A., ten Heggeler, M., Uijlenhoet, R., Delobbe, L., Dierickx, P. de Wit, M., 2005. A preliminary investigation of radar rainfall estimation in the Ardennes region and a first hydrological application for the Ourthe catchment. Nat. Hazards Earth Syst. Sci., 5, 267–274.

Brádka, J., Dřevikovský, A., Gregor., Z., Kolesár, J., 1961. Weather over the territory of Bohemia and Moravia in typical weather situations. Hydrometeorologický ústav, Prague, 31 p. (In Czech.)

Danko, M., Holko, L., Kostka, Z., Tachecí, P., 2015a. Simulation of snow water equivalent, snowmelt rate and runoff in mountain catchment during winter period. Acta Hydrologica Slovaca, 16, 1, 42–50. (In Slovak.)

Danko, M., Holko, L., Kostka, Z., Krajčí, P., Hlavčo, J., 2015b. Long-term simulation of snow water equivalent in mountain catchment using MIKE SHE / MIKE 11. Acta Hydrologica Slovaca, 16, 227–234. (In Slovak.)

Espinosa, B., Hromadka, T.V., Perez, R., 2015. Comparison of radar data versus rainfall data. MethodsX, 2, 423–431.

Fairman, J.G., Schultz, D.M., Kirshbaum, D.J., Gray, S.L., Barrett, A.I., 2015. A radar-based rainfall climatology of Great Britain and Ireland. Weather, 70, 153–158.

Germann, U., Galli, G., Boscacci, M., Bolliger, M., 2006. Radar precipitation measurement in a mountainous region. Q. J. Roy. Meteorol. Soc., 132, 1669–1692. DOI: 10.1256/qj.05.190

Gilewski, P., Nawalany, M., 2018. Inter-comparison of rain-gauge, radar, and satellite (IMERG GPM) precipitation estimates performance for rainfall-runoff modeling in a mountainous catchment in Poland. Water, 10, 1665.

Goudenhoofdt, E., Delobbe, L., 2016. Generation and verification of rainfall estimates from 10-yr volumetric weather radar measurements. J. Hydrometeor., 17, 1223–1242.

Hazenberg, P., Leijnse, H., Uijlenhoet, R., 2011. Radar rainfall estimation of stratiform winter precipitation in the Belgian Ardennes. Water Resour. Res., 47, 257.

Hess, P., Brezowsky, H., 1977. Katalog der Großwetterlagen Europas 1881-1976. 3rd Ed. Berichte des Deutschen Wetterdienstes, 113, 1–140. (In German.)

Hofstätter, M., Lexer, A., Homann, M., Blöschl, G., 2018. Large-scale heavy precipitation over central Europe and the role of atmospheric cyclone track types. Int. J. Climatol., 38, e497–e517. https:// doi.org/10.1002/joc.5386

Holko, L., Sleziak, P., Danko, M., Sleziak, P., 2021. Snowmelt characteristics in a pristine mountain catchment of the Jalovecký Creek, Slovakia, over the last three decades. Hydrol. Process., 35, e14128.

Holko, L., Hlavčo, J., Kostka, Z., 2014. Spatial distribution of precipitation in a mountain catchment. Acta Hydrologica Slovaca, 15, 102–109. (In Slovak.)

Holko, L., Kostka, Z., Danko, M., Liová, S., 2011. Hydrological Cycle in Mountain Environment. Životné prostredie, 45, 59–63.

Hrušková, K., Hlaváčiková, H., 2022. How to improve hydrological model forecast using precipitation data from small experimental basin. In: Book of Abstracts of the 18th Biennial Conference ERB 2022 Euromediterranean Network of Experimental and Representative Basins. Portoferraio, Elba Island, Italy, p. 37.

Kreklow, J., Tetzlaf, B., Burkhard, B., Kuhnt, G., 2020. Radar-based precipitation climatology in Germany – Developments, uncertainties and potentials. Atmosphere, 11, 217.

Marra, F., Morin, E., 2015. Use of radar QPE for the derivation of Intensity–Duration–Frequency curves in a range of climatic regimes. J. Hydrol., 531, 427–440.

McKee, J.L.; Binns, A.D., 2016. A review of gauge–radar merging methods for quantitative precipitation estimation in hydrology. Can. Water Resour. J., 41, 186–203.

Méri, L., Gaál, L., Bartok, J., Gažák, M., Gera, M., Jurašek, M., Kelemen, M., 2021. Improved radar composites and enhanced value of meteorological radar data using different quality indices. Sustainability, 13, 9, 5285.

Schleiss, M., Olsson, J., Berg, P., Niemi, T., Kokkonen, T., Thorndahl, S., Nielsen, R., Nielsen, J.E., Bozhinova, D., Pulkkinen, S., 2020. The accuracy of weather radar in heavy rain: A comparative study for Denmark, the Netherlands, Finland and Sweden. Hydrol. Earth Syst. Sci. Discuss., 1–42.

Slovak Hydrometeorological Institute (SHMI), 2021. Types of weather situations (http://www.shmu.sk/sk/?page=8) (In Slovak.)

Smith, J.A., Baeck, M.L., Villarini, G., Welty, C., Miller, A.J., Krajewski, W.F., 2012. Analyses of a long-term, high-resolution radar rainfall data set for the Baltimore metropolitan region. Water Resour. Res., 48, 616.

Sokol, Z., Szturc, J., Orellana-Alvear, J., Popová, J., Jurczyk, A., Célleri, R., 2021. The role of weather radar in rainfall estimation and its application in meteorological and hydrological modelling – A review. Remote Sens., 13, 351.

Villarini, G., Krajewski, W.F., 2010. Review of the different sources of uncertainty in single polarization radar-based estimates of rainfall. Surv. Geophys., 31, 107–129.

Received 5 August 2022
Accepted 27 October 2022