Continuity of long-term climate data series after the transition from manual to automatic weather station

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Abstract: In climatology, transitioning from conventional manual weather stations (MWS) to automatic weather stations (AWS) presents challenges in maintaining the homogeneity of long-term data series. At the Skalnaté Pleso Observatory (1778 m a.s.l., High Tatras), manual meteorological measurements have been conducted since 1943 using the same methods and devices at the same location. In 2014, the AWS Physicus was installed to record meteorological data parallelly with manual measurements. This study processed six years of parallel measurements (2017–2022) to derive corrections for AWS monthly atmospheric precipitation totals and maximum (Tmax), minimum (Tmin) and mean air temperatures (Tmean) measured in 2023. Two correction approaches were proposed: monthly regressions (MR) and cumulative distribution functions (CDF), including Generalized Extreme Value (GEV) distribution, normal distribution (GAUSS), and Gamma distribution (GAMMA). Analyses of monthly data revealed an underestimation of precipitation totals in AWS data, with a mean bias error (MBE) of −6.8 mm and a root mean squared error (RMSE) of 20.0 mm. The most suitable correction method was the MR, which decreased MBE to 1.5 mm and RMSE to 11.1 mm. AWS monthly air temperature data were overestimated by 0.1 °C, 0.3 °C, and 0.1 °C for Tmax, Tmin, and Tmean, respectively. For Tmax, correction using the MR and GEV methods reduced the MBE to 0.0 °C and achieved RMSE of 0.1 °C for both. After applying GAUSS, MBE and RMSE decreased to 0.1 °C. The most appropriate correction method for Tmin was the MR resulting in MBE of 0.0 °C and RMSE of 0.3 °C. For Tmean, the MR and GEV methods reduced the MBE to 0.0 °C and the RMSE to 0.1 °C for both methods. These results demonstrate that AWS monthly data, when corrected using the presented methods, have the potential to maintain the continuity of historical climate data series at Skalnaté Pleso Observatory.

Key words: air temperature, precipitation, measurements, differences, correction

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1. Introduction

High-quality, long-term climate data are required for monitoring and investigating variations, trends, forcing, and feedback in the climate system, which are crucial for understanding global climate change (*Schöner et al., 2012*). Mountain observatories around the world are unique sites for studying the climate of high-mountain regions (*Marty and Meister, 2012; Ludewig, 2021*). One such observatory with long-term climate measurements is the Skalnaté Pleso Observatory (SPO, 1778 m a.s.l.), situated at a unique position in the alpine tree line ecotone (ATE) in the High Tatra Mountains, Slovakia (Fig. 1). The climate series measured at SPO is an irreplaceable data source for research related to climate change in the ATE and its consequences for other spheres, particularly the biosphere and hydrosphere.

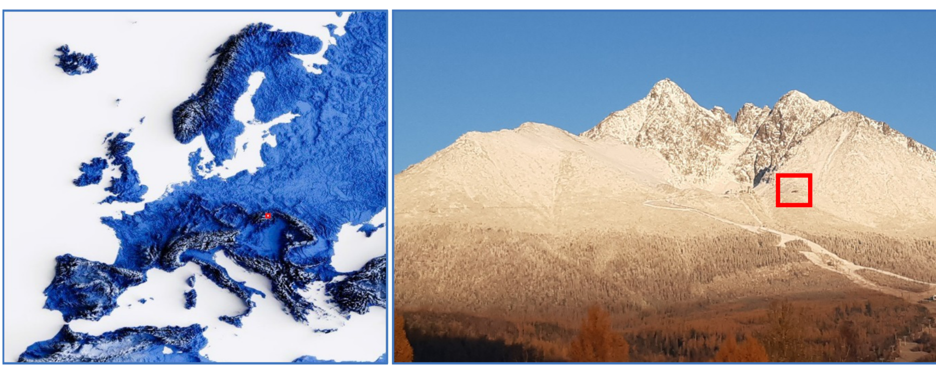

Fig. 1. Location of Skalnaté Pleso Observatory.

The establishment of SPO is connected to the construction of the cable car from Tatranská Lomnica through Skalnaté Pleso to Lomnický štít (Lomnický peak). The first meteorological measurements began in 1939 near the cable car station next to the tarn Skalnaté Pleso at 1769 m a.s.l. (*Smolen, 1990*). In 1943, climatologist and astronomer Dr. Antonín Bečvář (1901–1965) initiated the construction of a new observatory at an altitude of 1778 m a.s.l. (*Bičárová et al., 2013*), where systematic and regular observations have continued to the present day. Currently, the meteorological observatory SPO serves as the experimental workplace of the Earth Science Institute of the Slovak Academy of Sciences. For the entire period of its operation, a unique, more than 80-year-long database of meteorological data, measured using the same methods and devices at the same location, has been recorded. The automatic measuring system Physicus has operated since 2014 serving the parallel measurement data. To ensure the continuity of climatological recordings and to calculate the climatological standard normal for the next periods, data from automatic weather station (AWS) need to be processed and adjusted before the termination of the manual measurements (*WMO, 2017, Lukasová et al., 2023a*). Inhomogeneities in the measurements may result from changes in measurement locations, observing technology (hardware), shields, or software, which converts signals from instruments into meteorological variable values (*Caussinus and Mestre, 2004*).

Considering the limitations of SPO, the measuring errors of individual devices should be accounted for as well. For atmospheric precipitation, a parameter with significant differences between automatic and manual measurements (*Lukasová et al., 2023a*), the error could be about 5% (*Legates and DeLiberty, 1993; Habib et al., 2012; Talchabhadel et al., 2017; Pollock et al., 2018; Schleiss et al., 2020*). However, at locations with strong winds, the under-catch error may increase to about 10% for rainfall and 50% for snow (*Brandsma, 2014*). Tipping bucket rain gauges are susceptible to spurious readings due to disturbances, foreign objects entering the gauge, or similar issues. Losses may also occur due to unexpected failure of the gauge or a heating element at low temperatures (*Brandsma, 2014*). Furthermore, automatic rain gauges cannot reliably distinguish between rain and dew or frost, leading to an exaggerated number of days with small precipitation amounts (*WMO, 2017*).

Besides the inhomogeneities in data, other problems are associated with automatic measurements, especially at high-altitude meteorological observatories. The AWS is exposed to violent and frequent storms, particularly during summer, winter blizzards, and other extreme weather events, leading to more frequent equipment failures. In case of a failure or malfunction, it is often difficult to repair or replace the equipment, especially under adverse weather conditions and limited accessibility at high altitudes. For observatories in unique positions, this may result in data losses that are difficult to supplement with data from other stations.

At SPO, climatological normals for the periods 1961–1990 and 1991–2020 were derived from conventional manual measurements. In the event of discontinuing these manual measurements, a comparative analysis of differences between manual and automatic recordings and the proposal of suitable correction methods are necessary to ensure reliable data for the upcoming standard normal period of 2021–2050. Addressing issues related to data homogeneity, this study utilised parallel measurements of precipitation and temperature parameters from both manual weather station (MWS) and AWS during 2017–2022 to develop correction methods applicable to AWS data. The objective of this study was to validate the proposed methods using measurements from 2023.

2. Data and methods

2.1. Meteorological observatory at Skalnaté Pleso

In our study, we analysed the climate data series of precipitation totals and daily maximum, minimum, and mean air temperatures simultaneously measured by both automatic (AWS) and manual weather stations (MWS) at the Skalnaté Pleso Observatory (SPO, 1778 m a.s.l., High Tatras). Based on the two previous climatological normals (1961–1990 and 1991–2020) calculated from conventional measurements, the average annual air temperature increased from 1.7 to 2.8 °C, and precipitation totals increased from 1282 to 1477 mm (*Lukasová et al., 2023b*). At SPO, manual meteorological measurements have been consistently performed since 1943 using the same methods and devices at the same location. The AWS Physicus, which records meteorological data in parallel, was installed at the observatory in May 2014. The measurement equipment is detailed in Table 1 and Fig. 2.

According to national meteorological standards in Slovakia, manual measurements are conducted three times a day at 7:00, 14:00, and 21:00 LMT (Local Mean Time). Due to the geographical position of SPO, LMT is offset by 21 minutes from CET (Central European Time); thus, 7:00 LMT corresponds to 6:39 CET. Considering that manual measurements are conducted only three times daily, automatic measurements that are primarily stored in UTC (Coordinated Universal Time), were converted to LMT. Procedures for deriving monthly climatological parameters from meteorological data measured by both MWS and AWS were previously outlined in detail by *Lukasová et al. (2023a)*.

Table 1. Measuring devices at the manual and automatic meteorological station at Skalnaté Pleso Observatory for parallel measurements of meteorological elements used to calculate the climatological parameters.

Climatological parameter	Manual weather station	Automatic weather station
P – precipitation total	rain gauge (METRA 886)	tipping bucket rain gauge – MR3H
Tmax – maximum temperature	mercury-in-glass maximal thermometer	platinum resistance thermometers Pt100
Tmin – minimum temperature	minimal spirit thermometer	
Tmean – actual temperature	mercury-in-glass thermometer	

Fig. 2. Parallel manual and automatic measurements of air temperature (left) and atmospheric precipitation (right) at Skalnaté Pleso Observatory.

2.2. Correction methods for data measured by automatic system

The comparison of monthly climatological parameters in 2023 was conducted using two sets of data: i) original (measured) data, and ii) corrected data, taking the manual measurements as the reference. Excluding the first two years of the AWS trial period, which had several data gaps, this study processed six years of parallel measurements from 2017 to 2022 to derive corrections applicable to AWS data. These corrections are crucial for ensuring the continuity and homogeneity of the long-term conventional data series, which are essential for climatological analyses and calculating the subsequent climatological standard normal for the period 2021–2050.

Two approaches were utilised to minimise differences from the MWS data. The first approach involved regression models used to derive monthly adjustments, referred to as Monthly Regression (MR), from the 2017–2022 time series data for each of the 12 months separately. This resulted in 12 monthly adjustments for each parameter. The parameters of MRs for precipitation and temperatures are listed in Table 2.

Table 2. The parameters of linear monthly regressions: slope (a) and intercept (b) used in correction equations applied to the AWS data. Parameters are rounded to two decimal places.

Parameter	**P**		**Tmax**		**Tmin**		**Tmean**	
Month	**a**	**b**	**a**	**b**	**a**	**b**	**a**	**b**
I	1.47	−4.64	1.01	−0.16	1.02	−0.23	1.00	0.15
II	1.12	6.16	1.00	−0.22	1.00	−0.50	0.98	−0.26
III	0.61	30.03	1.05	−0.39	1.03	−0.15	1.03	0.08
IV	1.05	−0.83	1.00	−0.14	1.06	−0.22	1.00	−0.16
V	1.00	1.54	1.02	−0.20	1.00	−0.22	1.01	−0.19
VI	1.12	−6.16	0.98	0.31	1.04	−0.50	0.97	0.22
VII	1.10	−11.72	0.94	0.95	1.14	−1.46	1.02	−0.38
VIII	0.96	7.12	1.02	−0.35	1.07	−0.89	1.02	−0.34
IX	1.03	−0.40	0.97	0.33	1.02	−0.28	0.97	0.09
X	1.00	2.54	0.98	0.07	1.04	−0.23	0.98	−0.00
XI	1.07	2.43	1.03	0.23	1.05	−0.09	0.96	−0.09
XII	1.33	−15.80	1.01	0.01	0.98	−0.57	1.00	−0.10

The second approach – Quantile Mapping used three types of cumulative distribution functions (CDF), namely Generalized Extreme Value (GEV), normal (GAUSS) and Gamma (GAMMA) distribution functions to correct monthly precipitations. For correcting monthly temperature parameters, only the GEV and GAUSS distribution functions were applicable. The principle of QM is to match an AWS parameter value corresponding to a given cumulative probability with the equivalent cumulative probability in the distribution of the MWS data, which serves as the reference dataset. CDF matching bias correction functions were written in MATLAB. CDFs were generated using the data series from both the conventional and automatic stations for the period 2017–2022. In the next step, these theoretical distribution functions were applied to AWS data measured in 2023.

3. Results

3.1. Data gaps in annual series

The continual operation of the manual measuring system at SPO is ensured by the presence of an observer. Consequently, no data was missing from the MWS database over the analysed period from 2017 to 2023. However, instrument failures in the automatic measurement system caused data gaps during the analysed years (Table 3). The most significant data gaps occurred in 2022, when approximately 12% of the data, except for precipitation measurements, was missing. A considerable gap was recorded also in 2019 when around 5% of all parameters considered in this study were missed. Since the correction equations were derived from paired values, data without corresponding pairs in the parallel measurements were excluded.

Table 3. The percentage of missing daily data in individual years of parallel measurements of 2017–2023.

Year	2017	2018	2019	2020	2021	2022	2023
P	0.3	0.3	5.8	0.8	0.0	0.0	1.1
Tmax	0.3	0.3	5.2	0.8	0.0	11.8	1.1
Tmin	0.3	0.3	5.2	2.2	0.3	11.0	1.6
Tmean	0.3	0.3	5.2	0.8	0.5	12.1	1.1

3.2. Corrections of climatological parameters

Table 4 summarises the errors in AWS monthly data when MWS data were considered the reference. The comparison of original AWS data with parallel manual measurements revealed an underestimation of monthly precipitation totals and an overestimation of temperature parameters from the automatic system. The application of correction methods decreased both, the mean bias error (MBE) and the root mean squared error (RMSE) in all considered climate parameters.

Table 4. Mean bias error (MBE) and Root mean squared error (RMSE) of temperature and precipitation parameters measured by AWS (Orig. as original data) and adjusted using correction methods – Monthly regressions (MR) and Cumulative Distribution Functions using Generalized Extreme Value (GEV), normal distribution (GAUSS) and GAMMA distribution.

		P		Tmax		Tmin		Tmean	
		MBE	**RMSE**	**MBE**	**RMSE**	**MBE**	**RMSE**	**MBE**	**RMSE**
2017–2022	**Orig.**	−8.5	13.6	0.2	0.4	0.4	0.6	0.1	0.2
	MR	0.0	6.6	0.0	0.3	0.0	0.4	0.0	0.1
	GEV	−8.2	8.8	0.2	0.2	0.4	0.4	0.1	0.1
	GAUSS	−8.5	8.5	0.2	0.2	0.4	0.4	0.1	0.2
	GAMMA	−8.5	8.6	–	–	–	–	–	–
2023	**Orig.**	−6.8	20.0	0.1	0.1	0.1	0.4	0.1	0.1
	MR	1.5	11.1	0.0	0.1	0.0	0.3	0.0	0.1
	GEV	−1.6	18.9	0.0	0.1	−0.1	0.3	0.0	0.1
	GAUSS	−6.8	20.0	0.1	0.1	0.3	0.4	0.1	0.2
	GAMMA	1.3	18.8	–	–	–	–	–	–

Atmospheric precipitation. The AWS provided negatively biased monthly precipitation totals for almost the whole year of 2023. The automatic rain gauge recorded an annual total of 1695.6 mm, while the manual rain gauge collected 1777.5 mm of precipitation. The highest differences (ΔP) occurred in the winter months (Jan.–March), and the lowest ΔP was observed during the warm half of the year (Fig. 3). Problematic values in the winter months were caused by precipitation mainly in the form of snow. With heavy snowfall and strong wind gusts, the measurements of both rain gauges can be considered partially distorted.

After applying the Monthly Regressions, the MBE decreased from −6.8 to 1.5 mm and the RMSE decreased from 20.0 to 11.1 mm (Table 4). The RMSE of P_{MR} during the training period 2017–2022 was lower than in 2023 by 4.5 mm, however, the RMSE of the training period before the correction was also lower reaching only 13.6 mm. The differences in monthly precipitation before and after correction are shown in Fig. 3. The correction using the MR method reduced the standard deviation (SD) of ΔP from 29.2 mm to ΔP_{MR} 9.9 mm. After this correction, the annual precipitation total derived from AWS data exceeded the corresponding value from man-

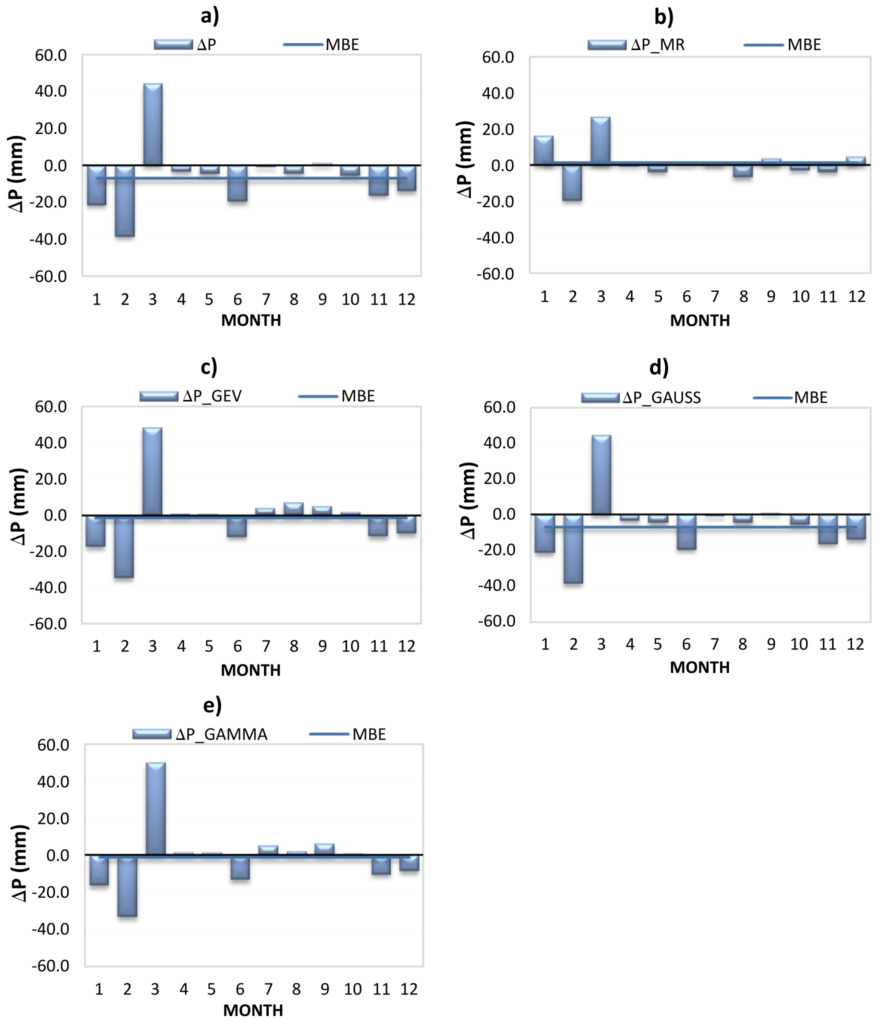

Fig. 3. Absolute differences between parallel AWS and MWS monthly precipitation totals (P) in 2023. Figures show the differences between P data before correction – ΔP (a), and after the correction by monthly regressions – ΔP_{MR} (b), GEV distribution – ΔP_{GEV} (c), GAUSS distribution – ΔP_{GAUSS} (d), and GAMMA distribution – ΔP_{GAMMA} (e).

ual measurements by 17.7 mm, which represents a relative difference of 1%.

None of the QM–CDFs brought comparable RMSE to those from the MR approach. Although the CDFs decreased the MBE to 1.3 mm using GAMMA, −1.6 mm using GEV and −6.8 mm using GAUSS distribution, their RMSE remained close to 20 mm (Table 4). The SD of corrected data was 19.6 mm for ΔP_{GAMMA} and ΔP_{GAUSS} and 19.7 mm for ΔP_{GEV}. However, the lowest difference in the annual total of −15.0 mm (−1%), was achieved by applying the GAMMA CDF.

Maximum air temperature. In 2023, the maximum temperature from AWS data was positively biased compared to that from MWS by 0.1 °C, with an RMSE of 0.1 °C. The average yearly maximum air temperature was 7.5 °C for MWS and 7.6 °C for AWS. The variation range of the original monthly ΔTmax was only 0.1 °C (Fig. 4a). The MR and GEV CDF correction methods decreased the MBE to 0.0 °C while maintaining an RMSE of 0.1 °C (Fig. 4, Table 4). The differences in RMSE between the correction methods were several hundredths of a degree Celsius, with the GAUSS CDF having the lowest RMSE, SD and variation range of differences compared

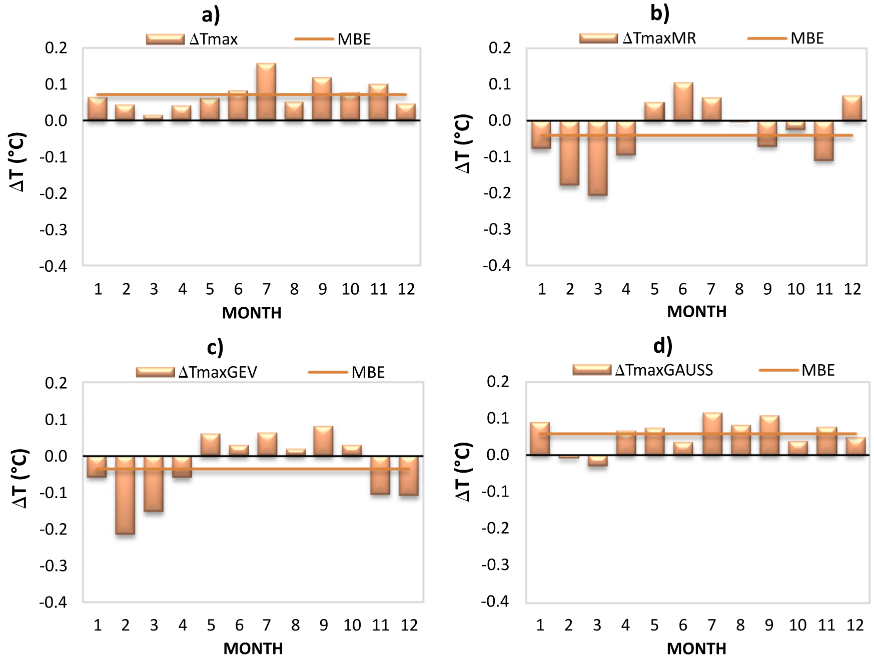

Fig. 4. Absolute differences between parallel AWS and MWS monthly maximum temperatures (Tmax) in 2023. Figures show the differences between Tmax data before correction – ΔTmax (a), and after the correction by monthly regressions – $\Delta Tmax_{MR}$ (b), GEV distribution function – $\Delta Tmax_{GEV}$ (c), and GAUSS distribution function – $\Delta Tmax_{GAUSS}$ (d).

to the other methods. Overall, in 2023, the CDFs applied to monthly Tmax yielded better results than during the training period 2017–2022 (Table 4).

Minimum air temperature. Tmin was the most biased temperature parameter, with an MBE of 0.3 °C and an RMSE of 0.4 °C in 2023. The average yearly minimum air temperature was 0.2 °C for MWS and 0.5 °C for AWS. The variation range in the monthly ΔTmin between measured data was 0.9 °C. The results of corrections are shown in Fig. 5. Correction using the MR method reduced the MBE to 0.0 °C and the RMSE to 0.3 °C but maintained the variation range at 0.9 °C, similar to that before the correction. The GEV CDF method achieved a similar RMSE of 0.3 °C with a variation range of 0.8 °C, but resulted in MBE of −0.1 °C (Table 4). Both methods struggled to adjust the negatively biased values in November and December, which increased the differences even more. The SDs of differ-

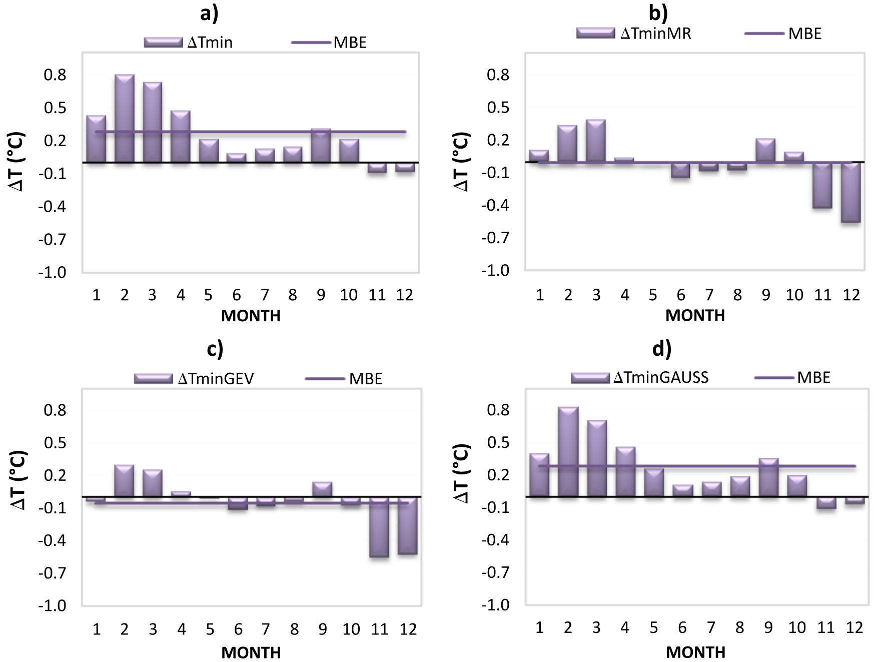

Fig. 5. Absolute differences between parallel AWS and MWS monthly minimum temperatures (Tmin) in 2023. Figures show the differences between Tmin data before correction – ΔTmin (a), and after the correction by monthly regressions – $\Delta\text{Tmin}_{\text{MR}}$ (b), GEV distribution function – $\Delta\text{Tmin}_{\text{GEV}}$ (c), and GAUSS distribution function – $\Delta\text{Tmin}_{\text{GAUSS}}$ (d).

ences before and after the corrections of Tmin were 0.3 °C for all correction methods and original values.

Mean air temperature. In 2023, the monthly mean air temperature data showed a positive bias in AWS Tmean compared to MWS Tmean (Table 4), with both the MBE and RMSE at 0.1 °C. The yearly mean temperature measured by MWS was 3.5 °C, while AWS recorded 3.6 °C. The results of corrections are shown in Fig. 6. Applying the MR method and GEV CDF for correction reduced the MBE to 0.0 °C while maintaining an RMSE of 0.1 °C (Table 4). Similar to $\Delta Tmax_{MR}$, the variation range of monthly $\Delta Tmean_{MR}$ was 0.3 °C, exceeding the variation range of ΔTmean before correction, while the correction with GEV CDF maintained it at 0.2 °C. The SDs in Tmean before and after the corrections were 0.1 °C for all, uncorrected and corrected Tmean values.

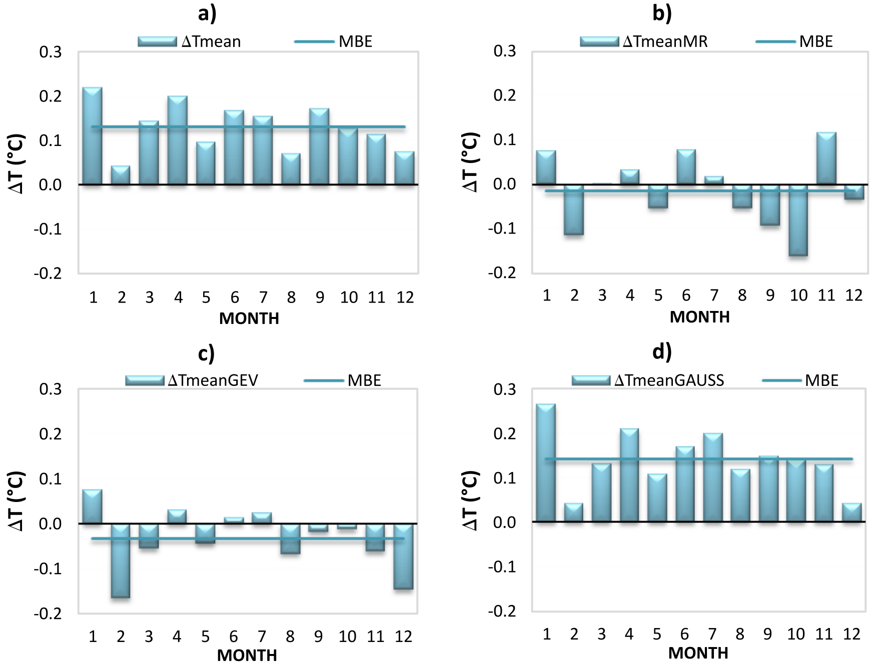

Fig. 6. Absolute differences between parallel AWS and MWS monthly mean temperatures (Tmean) in 2023. Figures show the differences between Tmean data before correction – ΔTmean (a), and after the correction by monthly regressions – $\Delta Tmean_{MR}$ (b), GEV distribution function – $\Delta Tmean_{GEV}$ (c), and GAUSS distribution function – $\Delta Tmean_{GAUSS}$ (d).

4. Discussion

The annual difference in precipitation totals measured in 2023 using AWS was −81.9 mm. The most effective correction approach was the MR method, which reduced the difference in yearly totals to 17.7 mm and decreased the RMSE from 20.0 mm to 11.1 mm. Precipitation measurements are typically affected by losses leading to under-catch (*Talchabhadel et al., 2017; Schleiss et al., 2020*). During the warm part of 2023, differences ranged from −19.4 to 1.1 mm, possibly due to evaporation losses or wind-induced errors (*Pollock et al., 2018*). Significant differences between precipitation measurement systems occurred mainly during winter months, concretely −38.5 mm in February and 44.2 mm in March. The substantial difference in March was caused primarily by the meteorological conditions in the month's final days. Snowfalls of 21 and 25 cm over two days accompanied by strong gusty winds contributed to unstable conditions for snow accumulation in rain gauges. The heated automatic rain gauge recorded more snowfall during this event than the standard rain gauge, where swirling snow likely had a more pronounced effect. These discrepancies in precipitation measurements during colder months could be partially addressed by installing a precipitation totaliser. The totaliser is constructed similarly to a manual rain gauge, with a sufficiently large collector to retain precipitation over time. It includes a pre-defined volume of water, frost protection (e.g., calcium chloride), and evaporation protection (e.g., Vaseline). Equipped with a windshield to prevent out-blow, especially of solid precipitation, the totaliser helps mitigate under-catch errors (*Groisman and Legates, 1994; Rasmussen et al., 2012; Brandsma, 2014*) in locations prone to strong winds like the Skalnaté Pleso Observatory. Positioned 2 to 4 m above ground level, the catchment area prevents complete burial by snow but may introduce height-of-rim-related errors due to vertical wind gradients (*Muchan and Dixon, 2019; Pollock et al., 2018*).

Transitioning to automated observations without corrections could introduce non-climatic jumps and alter long-term temperature records. In our study, the monthly air temperatures from AWS data measured in 2023 overestimated Tmax, Tmin and Tmean by 0.1, 0.3 and 0.1 °C, respectively. Differences in parallel temperature measurements were also described in studies *Fiebrich and Crawford (2009)*, *Kaspar et al. (2016)* and *Milewska and Vincent (2016).* This study focused on correcting temperature series inhomogeneities caused by different measuring instruments at the same location. Low MBE and RMSE in monthly Tmax data were achieved after corrections using all three methods, resulting in MBE and RMSE of 0.0 °C and 0.1 °C for MR and GEV, and MBE of 0.1 °C and RMSE of 0.1 °C for GAUSS CDF. The differences between methods were minimal, in the order of thousandths of a degree Celsius. For correcting Tmin, the MR method was the most appropriate, reducing MBE to 0.0 °C and RMSE to 0.3 °C. For Tmean, both MR and GEV methods resulted in MBE of 0.0 °C and RMSE of 0.1 °C. The MBE and RMSE in monthly temperatures in 2023 both before and after corrections showed minimal differences compared to the values observed in 2017–2022. The monthly regressions produced promising results, and there was an improvement seen with the use of cumulative distribution functions (Table 4).

The results presented indicate that correcting AWS monthly data using MR for atmospheric precipitation and Tmin, MR/GEV/GAUSS for Tmax, and MR/GEV for Tmean has the potential to maintain the continuity of historical climate data series at Skalnaté Pleso Observatory. However, further refinement of the equations will be necessary through a longer period of parallel measurements before full implementation.

5. Conclusion

In 2023, comparisons between parallel manual and automatic measurements revealed that AWS data underestimated monthly precipitation totals by −6.8 mm and overestimated air temperatures by 0.1 °C for Tmax, 0.3 °C for Tmin, and 0.1 °C for Tmean. The presented correction approaches successfully reduced the biases in AWS data and demonstrated potential for maintaining the homogeneity of the historical climate data series at Skalnaté Pleso Observatory. However, further refinement using longer periods of parallel measurements will be necessary before full implementation. Additionally, continuous parallel manual and automatic measurements at high-altitude meteorological observatories exposed to extreme weather events benefit from the 24/7 service of observers capable of handling minor device issues. However, in cases of a serious equipment failure like that in 2022, immediate repairs to the automatic system may be challenging due to unfavourable weather conditions or limited access to high mountains for other reasons. Such failures at observatories in unique locations may lead to data losses that are difficult to compensate for with data from other stations.

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