Adjustment of precipitation measurements using Total Rain weighing Sensor (TRwS) gauges in the cryospheric hydrometeorology observation (CHOICE) system of the Qilian Mountains, Northwest China (Postprint)

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Date: 2022-03-24T16:46:07+00:00

Abstract

Precipitation is one of the most important indicators of climate data, but there are many errors in precipitation measurements due to the influence of climatic conditions, especially those of solid precipitation in alpine mountains and at high latitude areas. The measured amount of precipitation in those areas is frequently less than the actual amount of precipitation. To understand the impact of climatic conditions on precipitation measurements in the mountainous areas of Northwest China and the applicability of different gauges in alpine mountains, we established a cryospheric hydrometeorology observation (CHOICE) system in 2008 in the Qilian Mountains, which consists of six automated observation stations located between 2960 and 4800 m a.s.l. Total Rain weighing Sensor (TRwS) gauges tested in the World Meteorological Organization-Solid Precipitation Intercomparison Experiment (WMO-SPICE) were used at observation stations with the CHOICE system. To study the influence of climatic conditions on different types of precipitation measured by the TRwS gauges, we conducted an intercomparison experiment of precipitation at Hulu-1 station that was one of the stations in the CHOICE system. Moreover, we tested the application of transfer functions recommended by the WMO-SPICE at this station using the measurement data from a TRwS gauge from August 2016 to December 2020 and computed new coefficients for the same transfer functions that were more appropriate for the dataset from Hulu-1 station. The new coefficients were used to correct the precipitation measurements of other stations in the CHOICE system. Results showed that the new parameters fitted to the local dataset had better correction results than the original parameters. The environmental conditions

of Hulu-1 station were very different from those of observation stations that provided datasets to create the transfer functions. Thus, root-mean-square error (RMSE) of solid and mixed precipitation corrected by the original parameters increased significantly by the averages of 0.135 (353%) and 0.072 mm (111%), respectively. RMSE values of liquid, solid and mixed precipitation measurements corrected by the new parameters decreased by 6%, 20% and 13%, respectively. In addition, the new parameters were suitable for correcting precipitation at other five stations in the CHOICE system. The relative precipitation (RP) increment of different types of precipitation increased with rising altitude. The average RP increment value of snowfall at six stations was the highest, reaching 7%, while that of rainfall was the lowest, covering 3%. Our results confirmed that the new parameters could be used to correct precipitation measurements of the CHOICE system.

Full Text

Adjustment of Precipitation Measurements Using Total Rain Weighing Sensor (TRwS) Gauges in the Cryospheric Hydrometeorology Observation (CHOICE) System of the Qilian Mountains, Northwest China

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Abstract: Precipitation represents one of the most critical indicators in climatology, yet measurements are subject to numerous errors arising from climatic conditions, particularly for solid precipitation in alpine and high-latitude regions where observed amounts frequently underestimate actual precipitation. To investigate the impact of climatic conditions on precipitation measurements in Northwest China’ s mountainous areas and assess the suitability of different gauge types, we established the Cryospheric Hydrometeorology Observation (CHOICE) system in 2008 across the Qilian Mountains, comprising six automated stations between 2960 and 4800 m a.s.l. The CHOICE system employs Total Rain weighing Sensor (TRwS) gauges tested in the World Meteorological Organization-Solid Precipitation Intercomparison Experiment (WMO-SPICE).

To examine climatic influences on various precipitation types measured by TRwS gauges, we conducted an intercomparison experiment at Hulu-1 station. Furthermore, we evaluated WMO-SPICE-recommended transfer functions using TRwS data from August 2016 to December 2020, deriving new coefficients optimized for the Hulu-1 dataset, which were then applied to correct measurements at other CHOICE stations. Results demonstrate that locally fitted parameters yield superior correction performance compared to original parameters. Environmental conditions at Hulu-1 station differed substantially from those at stations used to develop the original transfer functions, causing root-mean-square error (RMSE) for solid and mixed precipitation corrected with original parameters to increase significantly by averages of 0.135 mm (353%) and 0.072 mm (111%), respectively. Conversely, RMSE values for liquid, solid, and mixed precipitation corrected with new parameters decreased by 6%, 20%, and 13%, respectively. The new parameters also proved suitable for correcting precipitation at the other five CHOICE stations. Relative precipitation (RP) increments for different precipitation types increased with altitude, with snowfall showing the highest average RP increment (7%) across six stations, while rainfall exhibited the lowest (3%). These findings confirm that the new parameters can effectively correct precipitation measurements throughout the CHOICE system.

Keywords: automatic weather stations; Total Rain weighing Sensors; precipitation correction; transfer function; Qilian Mountains

Citation: ZHAO Yanni, CHEN Rensheng, HAN Chuntan, WANG Lei. 2022. Adjustment of precipitation measurements using Total Rain weighing Sensor (TRwS) gauges in the cryospheric hydrometeorology observation (CHOICE) system of the Qilian Mountains, Northwest China. Journal of Arid Land, 14(3): 310–324. https://doi.org/10.1007/s40333-022-0010-3

1 Introduction

Precipitation constitutes essential data for climatology, ecology, hydrology, weather forecasting, and cryosphere research [?, ?, ?, ?]. Accurate precipitation data are indispensable for water balance estimation, glacier change studies, hydrological process analysis, and ecological protection in mountainous regions [?, ?, ?, ?]. However, significant errors exist in precipitation observations [?]. Systematic measurement errors primarily result from wind-induced loss, wetting loss, and evaporation loss [?, ?]. Factors contributing to precipitation undercatch include wind speed, gauge type, wind shields, and precipitation crystal characteristics, with wind being a primary cause of snow undercatch [?, ?, ?, ?]. Moreover, precipitation in high-altitude mountains and boreal regions with extended winter seasons is substantially undercaught [?, ?, ?].

To address precipitation undercatch in manual measurements and establish standard methods for solid precipitation observation, the World Meteorological Organization (WMO) conducted a solid precipitation measurement intercomparison from 1985 to 1993. During this experiment, the International Organizing Committee designated the double fence intercomparison reference (DFIR)—comprising a manual Tretyakov gauge surrounded by an octagonal vertical double fence—as the reference standard for solid precipitation measurement. Researchers subsequently developed transfer functions (adjustments) to correct measurements of different precipitation types, primarily expressed as functions of wind speed [?, ?, ?, ?].

Following the initial WMO intercomparison, various automated snowfall measurement systems were designed and implemented, with weighing gauges representing a primary type of automated precipitation gauge [?]. A 2008 survey by WMO' s Commission for Instruments and Methods of Observation (CIMO) identified five automatic weighing gauge types in operation: OTT Pluvio2, T-200B Geonor, TRwS MPS system, VRG101 Vaisala, and MRW500 Meteoservis [?]. Although automatic instruments offer advantages such as real-time monitoring and improved accuracy, snowfall measurement errors are often overlooked, frequently ranging from 20% to 50% under windy conditions [?]. To assess automated system performance across different climate regimes and recommend appropriate field reference systems for unattended stations, CIMO initiated the Solid Precipitation Intercomparison Experiment (SPICE) in 2010 [?, ?]. SPICE incorporated more experimental sites with diverse climate regimes and automatic instruments than previous WMO intercomparisons. In SPICE, a single-Alter shielded automatic gauge surrounded by an octagonal double fence was designated as the double fence automatic reference (DFAR) standard for automated systems [?]. Transfer functions for automated measurements were developed as functions of both wind speed and air temperature [?, ?, ?]. Wolff et al. [?] created a continuous adjustment function for winter precipitation measurements at the Norwegian SPICE site. Kochendorfer et al. [?] developed and tested "universal" transfer functions using datasets from eight SPICE sites during winter periods from 2013–2014 to 2014–2015 to minimize errors in single-Alter shielded and unshielded weighing gauge measurements. Reverdin et al. [?] detailed data quality control and precipitation event selection methods. Kochendorfer et al. [?] tested and recommended transfer functions for all WMO-SPICE weighing gauges and shield configurations, demonstrating that previously developed functions could be widely applied. Smith et al. [?] evaluated WMO-SPICE transfer functions using additional winter season data from 2015–2016 to 2016–2017, finding that function performance varied by site and shield configuration.

In China, a precipitation intercomparison experiment between the Chinese standard precipitation gauge (CSPG) and Hellmann gauge was first conducted in the Tianshan Mountains during the WMO solid precipitation intercomparison (1985–1993) [?]. Yang et al. [?] developed CSPG transfer functions using 10-m wind speed data from Daxigou meteorological station. These international intercomparison achievements laid the foundation for subsequent precipitation measurement error correction work in China. Ren and Li [?] quantified various precipitation measurement errors through intercomparison experiments at 30 reference stations and established correction methods, particularly for wind-induced errors. Ye et al. [?] corrected CSPG measurement errors using long-term daily data from 726 meteorological stations during 1951–2004. In 2008, Chen et al. [?] established a precipitation intercomparison field (Hulu-1 station) in the Hulu Watershed of the Qilian Mountains to investigate how complex and variable climatic and environmental conditions affect different precipitation type measurements.

At Hulu-1 station, Chen et al. [?] compared rain, snow, and mixed precipitation measurements from CSPG with various shields and developed adjustment functions for unshielded and single-Alter shielded CSPG using a DFIR-shielded CSPG (CSPGDF) as the reference standard. In 2014, a Total Rain weighing Sensor 204 (TRwS204) equipped with a single-Alter shield (TRwSSA) was installed at Hulu-1 station. Subsequently, Zheng et al. [?] tested Kochendorfer et al.' s [?] transfer functions at Hulu-1 station using TRwSSA gauge data with CSPGDF as the reference standard. However, performance evaluation was challenging due to different gauge types and random errors. Zheng et al.' s [?] study on TRwS204 error correction was limited by CSPGDF observation frequency, allowing only daily precipitation data correction. Additionally, different gauges may introduce measurement errors, increasing correction result uncertainty. Therefore, an automatic reference standard was necessary to improve TRwSSA gauge correction accuracy.

After establishing a TRwS204 gauge reference standard in 2016, hourly precipitation measurements from TRwSSA gauges could be corrected, eliminating errors caused by different gauge types. To improve TRwS204 gauge measurement accuracy and understand climatic condition impacts on TRwS204 precipitation measurements, we conducted a precipitation observation intercomparison experiment with TRwS204 gauges at Hulu-1 station in the Hulu Watershed. This experiment was crucial for correcting automatic weighing gauge measurements in the Qilian Mountains and understanding observation errors in high-mountain areas. Since previous studies only tested transfer functions with wind speed and air temperature variables, we evaluated the applicability of all "universal" transfer functions recommended by WMO at this station. This study aimed to understand how climatic conditions affect TRwS204 gauge measurements for all precipitation types (rain, snow, and mixed precipitation). Additionally, we tested Kochendorfer et al.' s [?] "universal" transfer functions using TRwSSA gauge data and computed new coefficients better suited for TRwSSA gauges at our study site. These new parameters could correct precipitation measurements from other TRwS204 and TRwS504 gauges in the CHOICE system within the Hulu Watershed of the Qilian Mountains, China.

2.1 CHOICE System

The CHOICE system was established in 2008 in the Hulu Watershed of the Qilian Mountains, providing long-term, high-density meteorological datasets at altitudes of 2960–4800 m a.s.l., including glacier, snow, and permafrost hydrology data [?]. The system commonly used TRwS gauges—three TRwS204 gauges and four TRwS504 gauges. Each station featured a meteorological tower (Fig. 1).

The six observation stations, designated Hulu-1 through Hulu-6, are described in Table 1. All seven TRwS gauges operated without heating because heating gauge inlets would rapidly consume batteries, which could not be replaced promptly due to hazardous winter road conditions. Antifreeze was necessary for all weighing gauges to ensure collected water remained liquid, preventing instrument damage and data errors. Machine oil was also used to reduce evaporation. One TRwS gauge was surrounded by a DFIR shield, while others were equipped with single-Alter shields. TRwS504 capacity was 250 mm, while TRwS204 capacity was 750 mm. Orifice areas were 500 cm^2 for TRwS504 and 200 cm^2 for TRwS204. Wind speed (1405-PK-052, Gill Instruments Limited, UK), air temperature, and relative humidity (HMP155A, Vaisala, Inc., Finland) were measured at 1.5 and 2.5 m heights at each station.

2.2 Hulu-1 Station

Hulu-1 station (38°16 N, 99°52 E; 2980 m a.s.l.) is located on flat grassland in a valley near the Qilian Alpine Ecology and Hydrology Research Station, Northwest Institute of Eco-Environment and Resources (NIEER), Chinese Academy of Sciences, facilitating manual precipitation observations. We selected this station for intercomparison experiments between manual and automatic gauges and among different automatic weighing gauge types. The altitude difference around the station reaches approximately 1860 m. The station experiences low average wind speed (Table 1), with average snow depth from August 2016 to December 2020 of about 2 cm. Blowing or drifting snow is rarely observed [**?**]. In this study, we conducted precipitation measurement intercomparison experiments using TRwS204 at the station [**?**, **?**, **?**].

Instruments at Hulu-1 station (Fig. 1b) included three CSPGs with different shields, two CSPGs in pits, a single-Alter shielded TRwS204 (TRwSSA; Fig. 1c), a single-Alter shielded TRwS204 surrounded by a DFIR shield (TRwSDF; Fig. 1d) as the reference standard, a Tretyakov-shielded Geonor T-200B weighing gauge, and two automatic weather stations (Fig. 1b). TRwSSA height was approximately 0.7 m, while TRwSDF installation height was 3 m. Wind speed, air temperature, and relative humidity at 1.5 and 2.5 m heights were measured by automatic sensors on a meteorological tower (AMT-1 in Figure 1e). Another meteorological tower collected wind speed, air temperature, and relative humidity at 0.7 and 10.0 m heights (AMT-2 in Figure 1b). At the other five stations, TRwS gauge installation heights (approximately 0.7 m) differed from auxiliary meteorological data measurement heights (1.5 and 2.5 m) according to China Meteorological Administration (CMA) standards [**?**]. To correct all TRwS gauge measurements in the CHOICE system, auxiliary meteorological data at 1.5 m height were used at all stations.

From 2017 to 2020, average annual precipitation was 497.7 mm, occurring primarily during the warm season (May to September). At 1.5 m height, the annual mean temperature was 0.9°C, mean annual relative humidity was 56.2%, and mean annual maximum wind speed was 7.8 m/s.

2.3 Data Analysis

Manual quality control for all data involved several steps: (1) deleting data with repeated timestamps and filling missing values with "null" ; (2) removing values exceeding instrument-specified output ranges; (3) eliminating 30-min precipitation data recorded by weighing gauges when relative humidity was below 50%; and (4) screening out 30-min precipitation data less than 0.01 mm to reduce effects from fog and previous-hour precipitation. Additionally, based on observer records, we verified whether any data were mistakenly deleted, as precipitation occasionally occurred when relative humidity was below 50%.

We manually determined precipitation types according to CMA standards [?], with observations conducted twice daily at 08:00 and 20:00 (LST) at Hulu-1 station. However, precipitation and other meteorological data were recorded at half-hourly intervals, making manual observations insufficient for this study. Since precipitation type measurements were not performed at other stations, we used 30-min average air temperature (Tair) to determine precipitation types, evaluating solid precipitation (Tair < -2°C), mixed precipitation (-2°C $\leq$ Tair $\leq$ 2°C), and liquid precipitation (Tair $>$ 2°C) [?, ?].

Catch efficiency (CE), defined as the ratio of precipitation measured by TRwSSA to that measured by TRwSDF, requires a minimum threshold to constrain TRwSDF measurement errors [?]. This approach reduces measurement noise impact while maintaining a large precipitation event sample size. In Kochendorfer et al.' s [?] study, the DFIR precipitation threshold was iteratively increased from zero in 0.01 mm increments, with a simple linear transfer function calculated for each threshold. As shown in Figure 2, for each 0.01 mm threshold increase, the number of 30-min rainfall events (n) and standard deviation (σ) of the CE function were estimated, with minimum standard error (SE = $\sigma/\sqrt{\text{n}}$) occurring at 0.50 mm. Therefore, the minimum threshold for 30-min rainfall events was 0.50 mm. The same method determined minimum thresholds for snowfall (0.13 mm) and mixed precipitation (0.17 mm) using 30-min periods recorded by TRwSDF at Hulu-1 station. After these steps, rain, snow, and mixed precipitation events were identified.

By determining CE value ranges, we filtered precipitation events and selected representative measurements. Events with CE values between 0.50 and 1.30 were selected to test transfer functions, preventing large correction errors. From August 2016 to December 2020, we collected 1,551 precipitation events to test and evaluate transfer functions at Hulu-1 station (Table 2), with rainfall, snowfall, and mixed precipitation comprising 71%, 7%, and 22% of events, respectively.

2.4 Transfer Functions

The "universal" transfer functions were developed using datasets from single-Alter shielded and unshielded Geonor T-200B3 and OTT Pluvio2 gauges at eight test stations. Equation 1 is a function of air temperature and wind speed, representing a simple transformation of the sigmoidal transfer function tested by Wolff et al. [?] and introduced by Kochendorfer et al. [?]:

$$CE = \frac{1}{1 + \exp(-a - b \cdot v \cdot \tanh(c \cdot T_{air}))}$$

where v is average wind speed (m/s) and $T\_\{air\}$ is average air temperature (°C), both measured at the same height, and a, b, and c are coefficients fitted to the data. Precipitation type discrimination was unnecessary because air temperature served as a parameter in Equation 1. Coefficients $a = 0.0348$, $b = 1.366$, and $c = 0.779$ from Kochendorfer et al. [?] were used.

The exponential function was developed for solid and mixed precipitation using wind speed. Equation 2, described by Kochendorfer et al. [?], takes the form:

$$CE = a + b \cdot \exp(-c \cdot v)$$

where a, b, and c are fitted coefficients. Since some stations lacked precipitation type measurements, 30-min average $T\_\{air\}$ was used to determine precipitation types: snowfall at $T\_\{air\} < -2$°C, rainfall at $T\_\{air\} > 2$°C, and mixed precipitation at -2°C $\leq T\_\{air\} \leq 2$°C [?]. We applied coefficients for mixed-phase ($a = 0.668$, $b = 0.132$, $c = 0.339$) and snow ($a = 0.728$, $b = 0.230$, $c = 0.336$) from Kochendorfer et al. [?]. Additionally, a mean wind speed threshold of 7.2 m/s at gauge height was applied, replacing 30-min mean wind speed measurements exceeding this threshold [?].

2.5 Testing for Transfer Functions

We employed multiple statistics to evaluate "universal" transfer function performance depending on whether stations were equipped with the reference standard (TRwSDF). Four statistics estimated corrected measurement errors at Hulu-1 station: root-mean-square error (RMSE), mean bias, Pearson' s correlation coefficient (r), and the percentage of precipitation events with error less than 0.1 mm ($PE_{0 \cdot 1}$). RMSE quantified uncertainty in 30-min observed and corrected TRwSSA measurements relative to TRwSDF, evaluating transfer function relative performance. Bias represented the difference between average precipitation measurements from test and DFAR gauges. Pearson' s coefficient evaluated linear correlation between 30-min TRwSSA and TRwSDF measurements before and after correction. $PE_{0 \cdot 1}$, defined as the percentage of total event counts within the 0.1 mm threshold relative to total events [?], demonstrated how adjustments affected bias and uncertainty from an event-based perspective.

Kochendorfer et al. [?] applied 10-fold cross-validation when testing gauges at single stations. We used this method at Hulu-1 station, performing ten independent iterations where each iteration used 90% of data to derive function parameters and the remaining 10% to test transfer functions. Error statistics were averaged across all ten iterations.

Since the other five stations lacked DFIR standards, we used RP increment as an indicator to evaluate correction results. The equation follows [?]:

$$RP_{site} = \frac{P_{cor} - P_{mea}}{P_{mea}} \times 100\%$$

where *RP_{site}* is the relative precipitation increment for different stations, *P_{cor}* is corrected precipitation (mm), and *P_{me}*a is measured precipitation (mm).

3.1 Relationship Between CE and Wind Speed

Figure 3 illustrates relationships between catch efficiency (CE) and wind speed for rain, snow, and mixed precipitation. For liquid precipitation, CE values remained essentially constant initially, then decreased with increasing 30-min average wind speed (Fig. 3a). When average wind speed exceeded 3 m/s, CE values declined with wind speed increase. At mean wind speeds between 4 and 6 m/s, the median CE value was 0.87, relatively high under high wind speeds. Numerous outliers appeared in Figure 3a, particularly at low wind speeds where CE values were significantly scattered. At this station, snowfall could occur at air temperatures above 0°C, increasing dataset scatter. Additionally, the scarcity of rainfall events under high wind speeds resulted in decreasing data scatter with increasing wind speed.

For solid precipitation, CE values decreased slowly with increasing 30-min average wind speed, with scattered points concentrated primarily at wind speeds of 1-3 m/s (Fig. 3b). Under high wind speeds (4-6 m/s), the median CE value was 0.88, higher than that for rainfall. Rainfall might also occur when air temperature was below −2°C, partially explaining CE scatter for snowfall. Similar to the lack of rainfall events under high wind speeds, few snowfall events occurred under high wind speeds, resulting in decreased data scatter with increasing wind speed.

For mixed precipitation, CE values decreased noticeably with increasing 30-min average wind speed, though median CE values remained high when mean wind speed exceeded 4 m/s (Fig. 3c). At wind speeds between 5 and 8 m/s, the median CE value for mixed precipitation was 0.85. CE data were also scattered, as rainfall and snowfall could occur within the 30-min average air temperature range of mixed precipitation occurrences, making data scattering dependent on precipitation types.

3.2 Correlation Between TRwSSA and TRwSDF

Figure 4 shows strong correlation between TRwSSA and TRwSDF measurements, with R^2 values for all precipitation types approaching 1. Although rainfall scatter points plotted near the 1:1 diagonal, RMSE was 0.134 mm, higher than for solid and mixed precipitation (Figs. 4b, 4c, 4d). Mixed precipitation points were more scattered than rainfall and snowfall points. Overall, significant correlations existed between TRwSSA and TRwSDF regardless of precipitation type.

3.3 Testing Results

We used the Hulu-1 station dataset to fit new parameters more suitable for TRwSSA gauges. Significant differences emerged between adjusted results from "universal" transfer functions and those from new parameters (Fig. 5).

For liquid precipitation, only Equation 1 could correct measurements (Fig. 5a). RMSE values corrected by original and new parameters both decreased to 0.130 mm and 0.126 mm, respectively, with adjusted bias values near 0.000 mm for both. These results showed significant improvement in precipitation data corrected with both original and new parameters. Although corrected r and $PE_{0\cdot1}$ values remained unchanged, total liquid precipitation increased, with a difference of 7.83 mm between adjusted and reference rainfall.

For mixed precipitation, accuracy decreased when corrected by original parameters but improved with new parameters (Fig. 5b). Using original parameters, corrected RMSE for Equations 1 and 2 significantly exceeded 0.1 mm, reaching 0.116 mm and 0.156 mm, respectively, with adjusted bias values increasing substantially. Additionally, $PE_{0\cdot1}$ values corrected by Equations 1 and 2 decreased to 0.709 and 0.630, respectively. The substantial differences in environmental conditions among stations rendered the "universal" transfer functions unsuitable for correcting Hulu-1 station measurements. However, transfer functions with new parameters showed better performance, reducing adjusted RMSE by 11% and 16% for Equations 1 and 2, respectively, with corrected bias values near 0.000 mm.

For solid precipitation, accuracy decreased when corrected by "universal"transfer functions but improved with new parameters (Fig. 5c). Using original parameters, adjusted RMSE exceeded 0.160 mm, and corrected bias absolute values exceeded 0.100 mm. Adjusted $PE_{0\cdot1}$ using Equation 2 decreased by 25% (Fig. 5d), indicating that "universal" transfer functions were unsuitable for correcting solid precipitation at Hulu-1 station. New parameters fitted to local data were more appropriate for adjusting snowfall, reducing RMSE by 20% and yielding adjusted bias values near 0.000 mm.

Overall, new parameters fitted to Hulu-1 station precipitation measurements showed superior performance, calculated using solid, liquid, and mixed precipitation data from TRwS204 at the CHOICE system station. New coefficients for

Equation 1 were $a = 0.017$, $b = 0.280$, and $c = 0.714$, with 30-min average wind speed at 1.5 m height ranging $0 \leq v \leq 6$ m/s. New coefficients for Equation 2 were $a = 0.010$, $b = 0.888$, $c = 0.966$ for snowfall and $a = -0.010$, $b = -0.459$, $c = 1.012$ for mixed precipitation. For snowfall, 30-min average wind speed at 1.5 m height ranged $0 \leq v \leq 5$ m/s, and for mixed precipitation, $0 \leq v \leq 6$ m/s. These new coefficients were applied to correct rain, snow, and mixed precipitation throughout the CHOICE system.

3.4 Application of the New Parameters to the CHOICE System

We first applied new parameters to TRwS204 and TRwS504 gauges under similar environmental conditions to evaluate new transfer function performance, as TRwS504 gauges were primarily installed above 3500 m a.s.l. while new parameters were derived from TRwS204 gauges. Applicability of new parameters to higher-altitude TRwS504 gauges depended on correction results. Since all precipitation types at CHOICE system stations required correction, tests were conducted using Equation 1. Three observation stations—Hulu-1, Hulu-2, and Hulu-3—had similar elevations and predominantly grassland landscapes (Table 1). Precipitation at each station was dominated by liquid precipitation, accounting for over 70% of total precipitation. During precipitation, these stations experienced low wind speed and high air temperature (Tables 2 and 3). Figure 6 shows correction results for TRwS204 and TRwS504 gauges using new parameters under similar environmental conditions. The three stations exhibited highest RP values for snowfall and lowest for rainfall (Fig. 6). RP values for solid and mixed precipitation at Hulu-3 station were similar to those at Hulu-1 station, while liquid precipitation RP values differed substantially between the two stations. Hulu-2 station showed higher RP values for all precipitation types than other stations, particularly for snowfall.

New parameters performed better at higher-altitude stations (Hulu-4, Hulu-5, and Hulu-6) (Fig. 6). Solid precipitation RP values were highest, while liquid precipitation RP values were lowest. RP values for different precipitation types increased with altitude. Despite varying environmental conditions among stations, new parameters improved rain, snow, and mixed precipitation measurements, demonstrating their applicability for correcting observations across the entire CHOICE system.

4.1 Factors Impacting Precipitation Measurements at Hulu-1 Station

Hulu-1 station has the lowest elevation in the Hulu Watershed and is surrounded by high mountains with large altitude spans, resulting in low average wind speed. Low elevation and high air temperature lead to high liquid precipitation percentages at Hulu-1 station. During precipitation, most wind speeds measured at TRwSSA orifices were lower than those at 1.5 m height, yielding high CE values for liquid, solid, and mixed precipitation. Since average wind speeds during precipitation were mainly concentrated in the 0–3 m/s range, CE value scatter for different precipitation types decreased with increasing wind speed. Scatter at low wind speeds may result from wind influence on particle size distributions of different precipitation types. Cai et al. [?] conducted numerical simulations of wind turbulence for CSPG (70 cm height) equipped with Alter and Tretyakov wind shields, finding that the vortex core area at the gauge top with a Tretyakov shield was smaller than with an Alter shield at low wind speeds, benefiting precipitation collection. At Hulu-1 station, more turbulent wind fields may exist above TRwSSA height under low wind speeds, affecting TRwSSA collection efficiency. Additionally, light precipitation events—defined as accumulative precipitation below 0.70 mm within a 30-min period [?]—accounted for a high proportion when average wind speed was 0–3 m/s. Among these light precipitation events, light snow and light mixed precipitation accounted for 96% and 72% of total events, respectively, while light rain accounted for 43% (Fig. 3a). These results indicate that light precipitation events, comprising a large proportion, may increase data scatter under the influence of wind fields above TRwSSA height. Furthermore, the relationship between particle size and wind around the gauge significantly impacts undercatch [?, ?]. However, lacking instruments to study particle size and wind field changes, we could not quantify resulting precipitation measurement errors.

Another factor may be precipitation type classification using average air temperature at Hulu-1 station. Located in a mountainous area with changeable climate, Hulu-1 station may experience snowfall at 30-min average air temperatures above 0°C and rainfall below 0°C. Therefore, defining the 30-min average air temperature range of −2°C to 2°C as mixed precipitation generated numerous mixed precipitation events, increasing data scatter. Research shows that average air temperatures for 30-min solid and liquid precipitation in the Hulu Watershed are 0°C and 3°C, respectively [?]. Liu and Chen [?] used digital photogrammetry to verify and correct the half-hourly air temperature threshold for separating precipitation into rain, snow, and mixed precipitation. After two-year observations (2012–2013) at basin scale, they concluded that the air temperature threshold between rain and snow in the Hulu Watershed was usually 0°C, while the threshold between liquid and mixed precipitation was not significant. This suggests that the average temperature range used by Kochendorfer et al. [?] for precipitation type classification introduced uncertainties into correction and assessment, increasing CE value scatter for observed liquid, solid, and mixed precipitation. Consequently, the accuracy of adjustment results from Kochendorfer et al.' s [?] "universal" transfer functions was reduced, while new parameters suited to local datasets performed better.

4.2 Effects of Environmental Conditions and Gauge Types on Precipitation Measurements

Compared with Hulu-1 station, Hulu-2 and Hulu-3 stations had similar environmental conditions but different automatic weighing gauges: TRwS504 at Hulu-2 station versus TRwS204 at Hulu-1 and Hulu-3 stations. TRwS204 and TRwS504 gauges differ in orifice area and capacity. Orifice area differences in these common gauge types had minimal effect on wind speed increase [?] and could be ignored in the CHOICE system. However, instrument sensitivity might relate to weighing gauge capacity differences [?]. Kochendorfer et al. [?] found higher RMSE and lower $PE_{0\cdot1}$ values for a 1500-mm single-Alter Geonor T-200B gauge compared to a 600-mm single-Alter Geonor T-200B gauge at the same station. Uncertainty arising from capacity effects on gauges likely occurred during observation and correction. Since the cause of this uncertainty was unclear, we could not distinguish it from other factors such as wind and air temperature. However, new transfer functions significantly improved liquid, solid, and mixed precipitation measurements at Hulu-2 station, indicating that TRwS204 and TRwS504 measurements could be adjusted by the new transfer functions.

Since Kochendorfer et al.' s [?] "universal" transfer functions primarily corrected solid precipitation, RP values for snowfall at the three stations (Hulu-1, Hulu-2, and Hulu-3) were highest. The lowest RP values at Hulu-1 station likely resulted from higher rainfall and lower wind speed during precipitation, causing high CE values. Despite substantially different environmental conditions between these stations and Hulu-1 station, higher-altitude stations (Hulu-4, Hulu-5, and Hulu-6) showed better new transfer function performance. Wind speed was the main factor affecting CE values of TRwS gauges at all six stations. Low wind speed during precipitation may have been the leading factor enabling new parameters to correct measurements at Hulu-4, Hulu-5, and Hulu-6 stations.

5 Conclusions

This study investigated climatic condition impacts on TRwS204 gauge measurements of different precipitation types and tested the applicability of "universal" transfer functions from Kochendorfer et al. [?] at Hulu-1 station. We calculated new parameters better suited to the local dataset and applied them throughout the CHOICE system for performance evaluation.

At Hulu-1 station, measured wind speed was not the actual wind speed affecting precipitation measurements, resulting in high CE values for different precipitation types at high wind speeds. Data scatter decreased with increasing wind speed due to the lack of precipitation events under high wind speeds. Significant CE scatter under low wind speeds can be attributed to wind field influence above the gauge affecting distribution of different precipitation types, and to air temperature ranging from −2°C to 2°C used for precipitation type classification. Consequently, new parameters were more suitable for correcting precipitation measurements at Hulu-1 station. Data correction for other CHOICE system stations using new parameters indicated improved liquid, solid, and mixed precipitation measurements. The new parameters can be used to correct precipitation measurements for the entire CHOICE system.

Acknowledgements

This study was funded by the National Natural Sciences Foundation of China (42171145, 41690141, 41971041, 42101120) and the Joint Research Project of Three-River Headwaters National Park, Chinese Academy of Sciences and Qinghai Province, China (LHZX-2020-11). The authors thank all colleagues who participated in field experiments.

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Note: Figure translations are in progress. See original paper for figures.