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Precipitation measurement intercomparison in the Qilian Mountains, Northeastern Tibetan Plateau

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Abstract

Systematic errors in gauge-measured precipitation are well-known but no reports have come from the Tibet Plateau. An intercomparison experiment was carried out from September 2010 to September 2014 in the Hulu watershed, northeastern Tibet Plateau. Precipitation gauges included a Chinese standard precipitation gauge (CSPG), a CSPG with Alter shelter (Alter), a Pit type gauge with the CSPG (Pit) and a Double-Fence International Reference with Tretyakov shelter and CSPG (DFIR). The intercomparison experiments show that the Pit gauge caught 1 % more rainfall, 2 % more mixed precipitation, 4 % less snowfall and 0.8 % more precipitation (all types) than the DFIR from September 2012 to September 2014. The Pit caught 4 % more rainfall, 21 % more snow and 16 % more mixed precipitation than the CSPG. The DFIR caught 3 % more rainfall, 27 % more snowfall, and 13 % more mixed precipitation than the CSPG, respectively. For rain and mixed precipitation, the catch ratios (CRs) for the gauges are ranked as follows: $\mathrm{CR_{Pit}} > \mathrm{CR_{DFIR}} > \mathrm{CR_{Alter}} > \mathrm{CR_{CSPG}}$. For snowfall, the CRs are ranked as follows: $\mathrm{CR_{DFIR}} > \mathrm{CR_{Pit}} > \mathrm{CR_{Alter}} > \mathrm{CR_{CSPG}}$. Catch ratio vs. 10 m wind speed indicates that with increasing wind speed from 0 to 4.5 m $\mathrm{s^{-1}}$, the $\mathrm{CR_{CSPG}}$ or $\mathrm{CR_{Alter}}$ decreased slightly. For mixed precipitation, the ratios of DFIR/Alter or DFIR/Pit vs. wind speed show that wind speed has no significant effect on catch ratio below 3.5 m $\mathrm{s^{-1}}$. For snowfall, the ratio of CSPG/DFIR or Alter/DFIR vs. wind speed shows that catch ratio decreases with increasing wind speed. The calibration equations for three different precipitation types for the CSPG and Alter were established with 10 m wind speeds based on the CR vs. wind speed analysis. Results indicate that combined use of the DFIR and the Pit as reference gauges for snow and rainfall, respectively, could enhance precipitation observation precision. Applicable regions for the Pit gauge or the DFIR as representative gauges for all precipitation types are present in China.

1 Introduction

Accurate precipitation data are necessary for better understanding of the water cycle. It has been widely recognized that gauge-measured precipitation has systematic errors mainly caused by wetting, evaporation losses and wind-induced undercatch, and snowfall observation errors are very large under high wind (Sugiura et al., 2003). It would affect the available water evaluation in a large number of economic and environmental applications (Tian et al., 2007; Ye et al., 2012).

Rodda (1967) compared the catch of an UK 5″ manual gauge exposed normally at the standard height of 30.5 m above ground, with a Koschmieder-type gauge exposed in a pit. The pit gauge caught 6 % more precipitation than the normally exposed gauge. In the second WMO precipitation measurement intercomparison (Rain, 1972–1976), the pit gauge with anti-splash grid was designated the reference standard for rain gauges (Goodison et al., 1998; Strangeways, 1998). In the third WMO precipitation measurement intercomparison (Snow, 1986–1993), the Double Fence International Reference (DFIR) with a shielded Tretyakov gauge was designated the reference standard snow gauges (Goodison et al., 1989, 1998; Sugiura et al., 2003). In the fourth WMO precipitation measurement intercomparison (Rain Intensity, 2004–2008), different principles were tested to measure rainfall intensity and define a standardized calibration procedure (Lanza et al., 2005; Sevruk et al., 2009). Considering the automation of precipitation measurements, the WMO Commission for Instruments and Methods of Observation (CIMO) organized the WMO Solid Precipitation Intercomparison Experiment (WMO-SPICE; Yang, 2014) to define and validate automatic field instruments as references for gauge intercomparison, and to assess automatic systems and the operational networks for precipitation observations. The WMO-SPICE project selected double fence gauges as the reference.

Although adjustment procedures and reference measurements were developed in several WMO international precipitation measurement intercomparisons (Goodison et al., 1998; Yang, 2014), these have not been tested in the Tibetan Plateau. Because precipitation is concentrated in warm season on the Tibetan Plateau and is infrequent in winter, additional attention must be paid to systematic errors of gauge measured precipitation. The DFIR has been operated as a reference at 25 stations in 13 countries around the world (Golubev, 1985), but deviations from the DFIR measurements vary by gauge type and precipitation type (Goodison et al., 1998). In China, the DFIR was compared with the CSPG and the Hellmann gauge in valley site of Tianshan (43°4′ N, 87°9′ E, 3472 m) from 1987 to 1992, without wind data at the site (Yang et al., 1991; Goodison et al., 1998). Consequently, the derived CSPG catch ratio equations were based on the 10 m height wind speed at open Daxigou Meteorological Station (43.06, 86.5° E, 3540 m; Yang, 1988; Yang et al., 1991). Wind speeds at the Daxigou open site and the Tianshan valley site are different, inducing uncertainty in the catch ratio equations established by Yang et al. (1991) for CSPG. As the Tibetan Plateau is an ecologically fragile region and the source of several large rivers in China and neighborhood countries, accurate precipitation data is urgently needed. Considering that no other intercomparison experiments have been conducted or reported from the Tibetan Plateau and around regions (Chen et al., 2006), here it presents four-years gauge intercomparison experiment in the Qilian mountains at northeastern Tibet Plateau, China, to establish calibration equations for the widely used CSPG and Alter gauges.

The CSPG is the standard manual precipitation observation gauge used by the China Meteorological Administration (CMA) at more than 700 stations since the 1950s. These precipitation data sets have been used widely without calibration. The Alter shield is used by the CMA to enhance catch ratios of automatic gauges, so the CSPG with an Alter shied (Alter) was selected as another intercomparison gauge. The Pit and the DFIR were selected as the reference gauges for rainfall and snowfall, respectively. The intercomparison experiments tested and assessed existing bias correction procedures for the CSPG and the Alter. Blowing snow and thick snow cover have traditionally limited the Pit's use as a reference gauge for snowfall and mixed precipitation. Snowfall is infrequent in China and snow depths rarely over 10 cm in most part of China, so the Pit gauge has strong potential as a reference gauge for mixed precipitation and snowfall.

The Pit and the DFIR catch ratios for snowfall and mixed precipitation are also compared. The CMA stations observe wind speeds at 10 m height, so the CSPG and Alter calibration equations are established with 10 m height wind speeds rather than gauge height wind speeds.

2 Data and methods

Precipitation intercomparison experiments (Fig. 1, Table 1) were conducted at a grassland site in the Hulu watershed in the Qilian mountains, northeastern edge of Tibet Plateau, China (99°52.9′, 38°16.1′, 2980 m), where a meteorological cryosphere-hydrology observation system (Chen et al., 2014) has been established since 2008. Annual precipitation is about 447 mm and concentrated in the warm season from May to September. The annual temperature is approximately 0.4 °C, with a July mean of 4.2 °C and a January mean of −4.1 °C.

Relevant variables such as air temperature (maximum, minimum and mean; $T_{\max}$, $T_{\min}$ and T_0) have been observed manually at the site since June 2009. A tower is used to measure wind speed (Lisa/Rita, SG GmbH; W_s) and air temperature (HMP45D, Vaisala) at 1.5 and 2.5 m heights in association with relative humidity (HMP45D, Vaisala) and precipitation etc. (Chen et al., 2014). The specific meteorological conditions at the site are shown in Table 1.

The intercomparison experiments included a CSPG (orifice diameter = 20 cm, height = 70 cm) and a CSPG with Alter shelter (Struzer, 1971). A Pit gauge (Sevruk and Hamon, 1984) with CSPG (Pit) was installed in September 2010. In September 2012, a Double-Fence International Reference with a Tretyakov shelter and a CSPG (DFIR; Goodison et al., 1998) was installed as reference (Fig. 1, Table 2). In the cold season (October to April), snowfall dominated the precipitation events and in warm season (May to September), rainfall dominated. The precipitation amount (P) is measured manually twice a day at 08:00 and 20:00 LT (Beijing time). In the cold season the funnel and glass bottle are removed from the CSPG and precipitation is weighed under a windproof box to avoid wind effects. In the warm season P is measured by volume.

To correct the gauge-measured precipitation, Sevruk and Hamon (1984) have given the general formula as:

$$P_c = KP_g + \Delta P_w + \Delta P_e + \Delta P_t = P_{DFIR} + \Delta P_w + \Delta P_e + \Delta P_t \quad (1)$$

where P_c is the corrected precipitation, K is the wind-induced coefficient and P_g is the gauge-measured precipitation. P_w is wetting loss, P_e is evaporation loss, P_t is trace precipitation and P_{DFIR} is DFIR-measured precipitation. The precipitation gauges in this work are CSPGs with the same P_g, P_w, P_e and P_t, thus P_{DFIR} can be used instead of KP_g in Eq. (1). For the CSPG, P_w is 0.23 mm for rainfall measurements, and 0.30 mm for snow and 0.29 mm for mixed precipitation (Yang, 1988; Yang et al., 1991).The CSPG design reduces P_e to a value less than other losses in the warm, rainy season (Ye et al., 2004). In winter, P_e is already small (0.10–0.20 mm day^{-1}) according to results in Finland (Aaltonen et al., 1993) and Mongolia (Zhang et al., 2004). A precipitation event of less than 0.10 mm is beyond the resolution of the China recorder and is recorded as a trace amount of precipitation (P_t). Ye et al. (2004) recommended assigning a value of 0.1 mm, regardless of the number of the trace observations per day.

Most important factor influencing precipitation measurement in high mountain conditions is wind, which is the focus of the present study. The WMO has given Eqs. (2)–(4) for gauge catch ratio (CR = $1/K = P_g/\text{DFIR}$, %) vs. daily wind speed (W_s, m s^{-1}) at gauge height, and daily maximum and minimum temperatures (T_{max}, T_{min}, °C) on a daily time step for various precipitation types (Yang et al., 1995; Goodison et al., 1998). These equations can be used over a great range of environmental conditions (Goodison et al., 1998).

$$\mathrm{CR}_{snow} = 103.1 - 8.67W_s + 0.3T_{max} \quad (2)$$

$$\mathrm{CR}_{mix} = 96.99 - 4.46W_s + 0.88T_{max} + 0.22T_{min} \quad (3)$$

$$\mathrm{CR}_{rain} = 100.0 - 4.77W_s^{0.56} \quad (4)$$

where CR_{snow} (%), CR_{mix} (%), and CR_{rain} (%) are catch ratios for snow, mixed precipitation, and rain (%), respectively; W_s is wind speed at gauge height ($\mathrm{m\,s^{-1}}$); T_{max} and T_{min} are daily maximum and minimum air temperatures (°C).

Yang et al. (1991) and Ye et al. (2007) have given Eqs. (5)–(7) for CSPG catch ratios vs. daily wind speed W_s ($\mathrm{m\,s^{-1}}$) at 10 m height:

$$CR_{snow} = 100\exp(-0.056W_s) \quad (0 < W_s < 6.2) \tag{5}$$

$$CR_{rain} = 100\exp(-0.04W_s) \quad (0 < W_s < 7.3) \tag{6}$$

$$CR_{mix} = CR_{snow} - (CR_{snow} - CR_{rain})(T_0 + 2)/4 \tag{7}$$

where T_0 is the daily mean air temperature.

In this field experiment, two aspects are focused. One is based on rainfall observations comparisons among the CSPG, Alter and Pit gauges to establish calibration equations for the CSPG and the Alter with 10 m height wind speeds. Another purpose is based on snow and mixed precipitation observation comparisons among the CSPG, Alter, Pit, and DFIR, to establish calibration equations for snow and mixed precipitation with 10 m height wind speeds.

3 Results

From September 2010 to September 2014, total 578 observations were recorded at the intercomparison site for CSPG, Alter and Pit, respectively (Table 3). Snow happened 67 times, mixed precipitation only happened 32 times, and rain happened 479 times during this period. From September 2012 to September 2014, a subset of 253 observations were recorded for the CSPG, Alter, Pit, and DFIR gauges (Table 3).

3.1 Precipitation gauge intercomparison for rainfall

The Pit was selected as the reference gauge, and 479 rainfall events recorded by three different gauges from September 2010 to September 2014 were used in the intercomparsion studies (Table 3). The Pit caught 4.7 % more rainfall than the CSPG, and 3.4 % more than the Alter.

For rainfall events from September 2012 to September 2014, the DFIR was selected as the reference gauge. The DFIR caught 3.4 % more rainfall than the CSPG, 2.5 % more than the Alter, and 1.0 % less than the Pit (Table 3). Comparative studies indicate that the Pit gauge CR is superior to that of the DFIR or the other gauges (Fig. 2).

3.2 Precipitation gauge intercomparison for mixed precipitation

Table 3 lists the primary intercomparison results for the 4 different gauges. The DFIR caught 13.4 % more mixed precipitation than the CSPG, 5.4 % more than the Alter, and 2.4 % less than the Pit from September 2012 to September 2014 (Table 3). Selecting the DFIR as the reference, Fig. 3 compares 17 mixed precipitation events among the DFIR and the other gauges (CSPG, Alter and Pit). Close liner relationships exist among the gauges. The Pit caught more mixed precipitation than the DFIR in two successive years, which means the Pit gauge could be used as reference gauge for mixed precipitation at the Hulu watershed experiment site. Figure 4a and b compares 32 mixed precipitation events between the Pit and the CSPG and the Pit and Alter, from which it notes the mixed precipitation amount differences for the Pit and CSPG or the Pit and the Alter range from 0.1 to 2 mm; no outliers and scatters appeared on the plots. Regression analysis reveals a close correlation between the Pit and the other gauges for mixed precipitation data. The linear relationship is statistically significant with 98 % confidence. Thus the Pit gauge instead of the DFIR could be selected as the reference gauge of mixed precipitation to calculate CRs for the CSPG and the Alter.

3.3 Precipitation gauge intercomparison for snowfall

From September 2012 to September 2014, total 26 field observations of snowfall were recorded (Table 3). Observations indicated that the DFIR caught 26.7 % more snowfall than the CSPG, 11.4 % more than the Alter, and 4.6 % more than the Pit. The difference of total snowfall between the DFIR and the Pit was only about 2.3 mm.

Selecting the DFIR as the reference, Fig. 5 compares 26 snow precipitation events among the DFIR and the other three gauges. Close linear relationships exist between the DFIR and each of the other three gauges. From the Fig. 5c, it could find the good liner correlation existed between the Pit and the DFIR, and the total precipitation difference was very small between these two gauges. Considering the fact that only two years of DFIR observation data are available, while the Pit gauge has four consecutive years of observations data, the Pit gauge was selected as the reference to calculate CRs for the CSPG and the Alter. From September 2010 to September 2014, the Pit caught 24.2 % more snow than the CSPG and 7.8 % more than the Alter. Figure 6a and b compares 67 snow precipitation events for the Pit with the CSPG and the Alter, which showed close linear relationships. In four consecutive years, the $\mathrm{CR}_{\mathrm{Pit}}$ ($P_{\mathrm{CSPG}}/P_{\mathrm{Pit}}$) of the CSPG is 0.80 (Table 3), which is close to the $\mathrm{CR}_{\mathrm{DFIR}}$ ($P_{\mathrm{CSPG}}/P_{\mathrm{DFIR}} = 0.79$) of the CSPG in two year observation results (Table 3). This means the Pit gauge could be used as the reference gauge for snow precipitation events at the experiment site.

3.4 Catch ratio vs. wind speed

Previous studies showed that wind speed during the precipitation period is the most significant variable affecting gauge catch efficiency (Metcalfe and Goodison, 1993; Yang et al., 1995; Goodison et al., 1998). Here the relationships of rain, mixed precipitation, and snow catch ratios to wind speed during the precipitation periods are analyzed. To minimize ratio scatter of among different gauges, precipitation events greater than 3 mm are normally selected in the ratio vs. wind analysis (Yang et al., 1995, 2014). In the Hulu watershed, most snowfall events are less than 3 mm. For this reason, precipitation greater than 1 mm was used in this study for catch ratio vs. wind studies. W_{s} at 10 m height was calculated using half-hourly wind speed data at 1.5 and 2.5 m heights, according to the Monin–Obukhov theory and the gradient method (Bagnold,1941; Dyer and Bradley, 1982):

$$\ln z_0 = \frac{W_{s2.5}\ln 1.5 - W_{s1.5}\ln 2.5}{W_{s2.5} - W_{s1.5}} \tag{8}$$

$$W_s = kW_{s1.5}, \qquad k = \frac{\ln(10.0/z_0)}{\ln(1.5/z_0)}. \tag{9}$$

3.4.1 Rainfall catch ratio vs. wind speed

Selecting the Pit gauge as the reference, Fig. 7 presents scatter plot of the CRs of CSPG/Pit and Alter/Pit vs. wind speed. The CRs vary from 0.8 to 1.1. With increasing wind speed, the CRs decreased slightly. The following two Eqs. (10) and (11) could be used to calibrate the rainfall data for the CSPG gauge or the Alter gauge.

$$\mathrm{CR}_{\mathrm{CSPG}} = -0.01 \cdot W_s + 0.989 \tag{10}$$

$$\mathrm{CR}_{\mathrm{Alter}} = -0.01 \cdot W_s + 0.998 \tag{11}$$

where $\mathrm{CR}_{\mathrm{CSPG}}$ is the CSPG catch ratio, $\mathrm{CR}_{\mathrm{Alter}}$ is the Alter catch ratio, W_s is the wind speed at 10 m height.

3.4.2 Mixed precipitation catch ratio vs. wind speed

Figure 5c shows that a good liner relationship existed between the Pit and the DFIR for mixed precipitation measurement. Figure 8a shows that the Pit/DFIR CR is approximately 1, and wind speed has little effect on the Pit gauge for mixed precipitation. Thus the Pit gauge was selected as the reference to establish a regression equation between the CSPG/Pit CR and wind speed. Figure 8b and c shows that the CSPG/Pit CR and the Alter/Pit CR decreased with increasing wind speed. Equations (12) and (13) were established to calibrate the CSPG or Alter gauge mixed precipitation data.

$$\mathrm{CR}_{\mathrm{CSPG}} = -0.051 \cdot W_{\mathrm{s}} + 1 \tag{12}$$

$$\mathrm{CR}_{\mathrm{Alter}} = -0.030 \cdot W_{\mathrm{s}} + 1 \tag{13}$$

where $\mathrm{CR}_{\mathrm{CSPG}}$ is the CSPG catch ratio, $\mathrm{CR}_{\mathrm{Alter}}$ is the Alter catch ratio, and W_{s} is the wind speed at 10 m height.

3.4.3 Snowfall catch ratio vs. wind speed

Figure 9a presents the scatter plot of the CSPG/DFIR CR vs. wind speed. The CR decrease from 1.0 to 0.6 when wind speed increased from 0.5 to 4.5 $\mathrm{m\,s^{-1}}$. The scatter plot of the CR of Alter/DFIR vs. wind speed shows that the CR decreased from 1.0 to 0.8 with increasing wind speed from 0.5 to 3 $\mathrm{m\,s^{-1}}$ (Fig. 9b). Wind speed has no significant effect on Pit/DFIR CR, and the CR values are around 1.0. From Fig. 9c it could be concluded that the Pit gauge can substitute as the reference gauge at the experiment site. Equations (14) and (15) could be used to calibrate the CSPG or Alter gauge snowfall data.

$$\mathrm{CR}_{\mathrm{CSPG}} = -0.081 \cdot W_{\mathrm{s}} + 1 \tag{14}$$

$$\mathrm{CR}_{\mathrm{Alter}} = -0.016 \cdot W_{\mathrm{s}} + 0.957 \tag{15}$$

where $\mathrm{CR}_{\mathrm{CSPG}}$ is the CSPG catch ratio, $\mathrm{CR}_{\mathrm{Alter}}$ is the Alter catch ratio, and W_{s} is the wind speed at 10 m height.

4 Discussion

4.1 Comparison with other studies

Yang et al. (1991) carried out a precipitation intercomparison experiment in valley site of Tianshan. Their results indicated that the ratios of DFIR/CSPG for snowfall and mixed precipitation were 1.222 and 1.160. In the Hulu watershed, the ratios of DFIR/CSPG for snowfall and mixed precipitation were 1.234 and 1.069, and the ratio of Pit/CSPG for snowfall and mixed precipitation is 1.199 and 1.078, respectively. Similar topographic features and shading induced lower wind speeds at both sites, which led to the similar catch ratios. For the Tianshan reference site, wind speed on rainfall or snowfall days never exceeds 6 $\mathrm{m\,s^{-1}}$ and 88 % of the yearly total precipitation took place with wind speeds below 3 $\mathrm{m\,s^{-1}}$. For the Hulu watershed site, wind speeds on precipitation days never exceeded 4.5 $\mathrm{m\,s^{-1}}$, and over 80 % of the precipitation events happened when wind speeds were below 3 $\mathrm{m\,s^{-1}}$.

As Ren and Li (2007) reported, among 30 comparison stations in China, the Pit caught 3.2 % (1.1–7.9 %) more rainfall and 11.0 % (2.2–24.8 %) more snowfall than the CSPG. Large wind-induced differences often appeared at the western mountainous stations. In our study, the Pit gauge got 4.7 % more rainfall, 24.2 % more snowfall, and 11.6 % more mixed precipitation than the CSPG from September 2010 to September 2014 (Table 3). The outcome presented in this study is similar with Ren and Li (2007) presented.

4.2 Possibility of the Pit gauge as a reference for solid precipitation

The Pit gauge is the WMO reference standard for liquid precipitation measurements and the DFIR is the reference standard for solid precipitation measurements (Sevruk et al., 2009). In this study, the Pit gauge performed superior than the DFIR for rainfall catch ratio and mixed precipitation catch ratios. For snowfall, the catch ratio for the Pit gauge is 0.96, close to the DFIR catch ratio. Thus the Pit gauge could serve as a reference for liquid and solid precipitation in the Hulu watershed. Considering the Pit gauge's greater simplicity and practicality, it could be more convenient for researchers and observers to use the Pit gauge as the standard reference for snow and mixed precipitation in other locations. Precipitation collected by the Pit gauge would be most affected when blowing or drifting snow occurred, and induce a faulty precipitation value (Ren and Li, 2007). Previous studies have indicates, however, that for most of China maximum snow depths in the past 30 years have been less than 20 cm (Li, 1999), and average snow depths were less than 3 cm (Li et al., 2008; Che et al., 2008). Figure 10 shows annual snowfall amounts and annual snowfall proportion distributions for 644 meteorological stations in China from 1960 to 1979, indicating that snowfall concentrated in the south-eastern Tibetan Plateau, northern Xinjiang province and north-eastern China. Statistical analysis indicates that for more than 94 % of stations, solid precipitation is less than 15 % of the annual precipitation amount. Scarcity of accumulated snow and little snowfall correlates to rare occurrence of blowing snow in most of China. The applicable regions for the Pit and the DFIR as reference gauges are shown in Fig. 11 based on CMA snowfall and snow depth data.

5 Conclusions

The precipitation intercomparsion experiment in the Hulu watershed indicates that the Pit gauge catches more rainfall, mixed precipitation and total precipitation than the DFIR. The catch ratios for rainfall and mixed precipitation can be ordered as follows: $\mathrm{CR}_{\mathrm{Pit}} > \mathrm{CR}_{\mathrm{DFIR}} > \mathrm{CR}_{\mathrm{Alter}} > \mathrm{CR}_{\mathrm{CSPG}}$. While in the snowy season, it follows the rule that better wind-shelter catch with more snow, and the catch ratios for snow can be ordered $\mathrm{CR}_{\mathrm{DFIR}} > \mathrm{CR}_{\mathrm{Pit}} > \mathrm{CR}_{\mathrm{Alter}} > \mathrm{CR}_{\mathrm{CSPG}}$. The catch ratio of the Pit vs. DFIR reaches 1.01 for solid and liquid precipitation.

In rainfall dominated south and central part of China, the Pit gauge could be used as the reference gauge with highest catch ratio. In north-east China, northern Xinjiang province and southeastern Tibetan Plateau where snowfall concentrates, the best choice for reference gauge would be the Pit for rainfall and DFIR for snowfall observations. For other regions with little snowfall or accumulated snow, the low cost of the Pit gauge gives it great potential as reference gauge instead of the DFIR.

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Table 1. Monthly climate values at the experimental site (2010–2012).

Element	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
P (mm)	3.5	2.5	11.0	8.8	67.7	69.6	87.1	111.6	57.7	24.0	2.7	1.0	447.2
T_0 (°C)	−4.1	−2.6	−1.5	0.7	2.3	3.7	4.2	4.0	2.7	0.5	−1.9	−3.8	0.4
T_{max} (°C)	−1.3	0.2	1.2	3.4	4.8	6.1	6.5	6.6	5.1	3.4	1.2	−0.6	3.0
T_{min} (°C)	−6.3	−4.9	−3.9	−1.7	0.2	1.6	2.3	1.9	0.6	−1.8	−4.2	−6.1	−1.9
$W_{\text{s1.5}}$ (m s^{-1})	0.60	0.65	0.77	0.85	0.81	0.66	0.61	0.60	0.64	0.60	0.69	0.65	0.68
$W_{\text{s2.5}}$ (m s^{-1})	0.60	0.67	0.81	0.92	0.88	0.72	0.68	0.67	0.72	0.66	0.73	0.67	0.73
E_0 (mm)	31.6	47.0	79.4	124.4	140.9	155.0	141.7	127.0	101.6	75.2	47.3	31.0	1102.2

Table 2. The precipitation measurement intercomparison experiment in Qilian mountains.

Gauge	Abbreviation	Size(φ stand for orifice diameter and h for observation height)	Start date	End date	Measure time
China standard precipitation gauge	CSPG	$\varphi = 20\,\text{cm}$, $h = 70\,\text{cm}$	Jun 2009	Sep 2014	20:00 and 08:00, LT
CSPG with Alter shelter (Struzer, 1971)	Alter	$\varphi = 20\,\text{cm}$, $h = 70\,\text{cm}$	Jun 2009	Sep 2014	20:00 and 08:00, LT
Pit gauge (Sevruk, 1984) with a CSPG	Pit	$\varphi = 20\,\text{cm}$, $h = 0\,\text{cm}$	Sep 2010	Sep 2014	20:00 and 08:00, LT
Double-Fence with CSPG (Goodison et al., 1998)	DFIR	$\varphi = 20\,\text{cm}$, $h = 3.0\,\text{m}$	Sep 2012	Sep 2014	20:00 and 08:00, LT

Table 3. Summary of daily observations at Hulu watershed intercomparison site, 2010–2014.

Date	Precipitation type	No. of events	Total precipitation and catch ratio (CR)							
			CSPG (mm)	CR	Alter (mm)	CR	Pit (mm)	CR	DFIR (mm)	CR
Sep 2010–Sep 2014	All type	578	1925.0	0.94	1971.6	0.96	2046.0	1		
	rain	479	1697.2	0.95	1719.8	0.97	1777.5	1		
	mixed	32	114.8	0.90	121.5	0.95	128.1	1		
	snow	67	113.0	0.80	130.3	0.93	140.4	1		
Sep 2012–Sep 2014	All type	253	1004.9	0.95	1021.9	0.97	1061.9	1.01	1053.1	1
	rain	210	917.2	0.97	925.0	0.98	957.9	1.01	948.1	1
	mixed	17	46.1	0.88	49.6	0.95	53.6	1.02	52.3	1
	snow	26	41.6	0.79	47.3	0.90	50.4	0.96	52.7	1

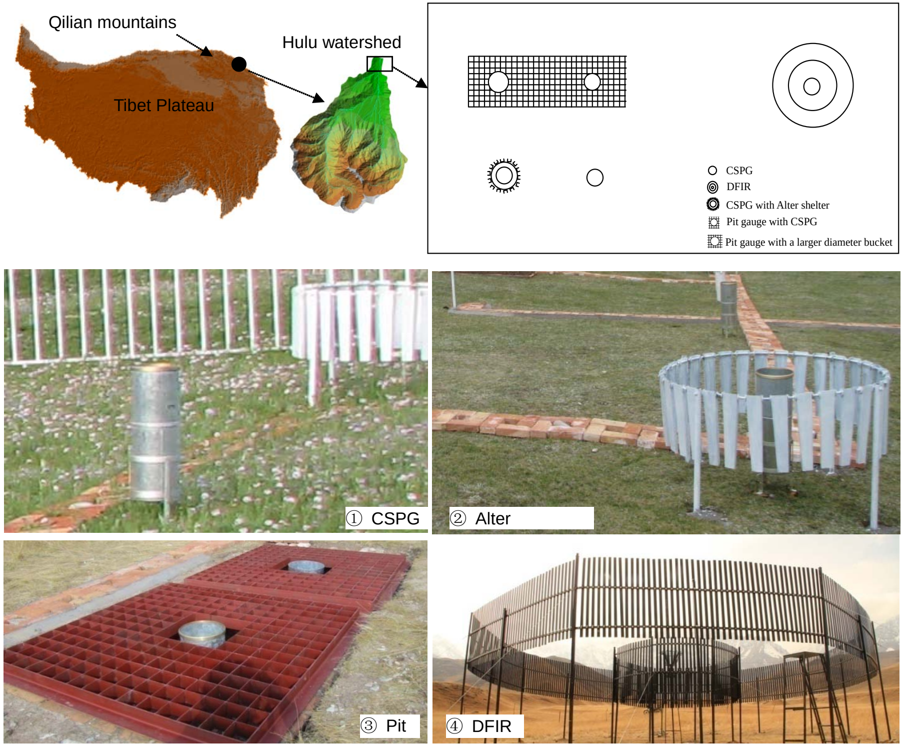

Figure 1. Precipitation gauge intercomparison experiment in the Qilian mountains, Tibetan Plateau.

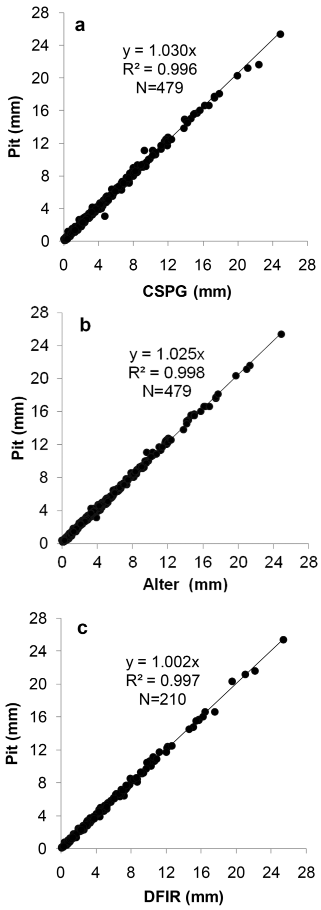

Figure 2. Scatter plots for rainfall of **(a)** the CSPG, **(b)** the Alter and **(c)** the DFIR vs. the Pit from September 2010 to September 2014.

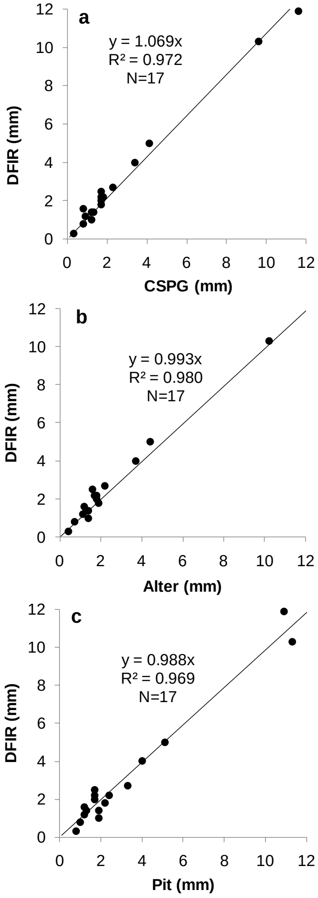

Figure 3. Scatter plots of mixed precipitation for **(a)** the CSPG, **(b)** Alter and **(c)** the Pit vs. the DFIR from September 2012 to September 2014.

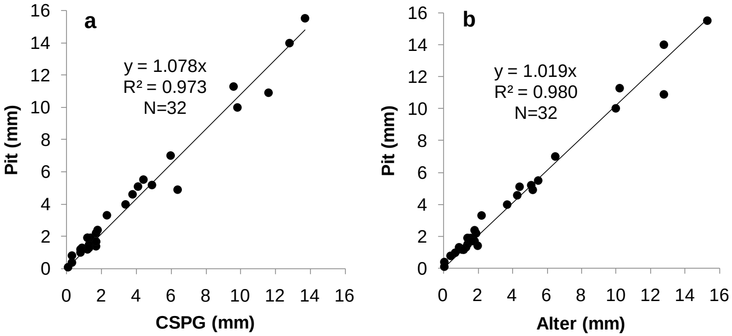

Figure 4. Scatter plots of mixed precipitation for **(a)** the CSPG and **(b)** the Alter vs. the Pit from September 2010 to September 2014.

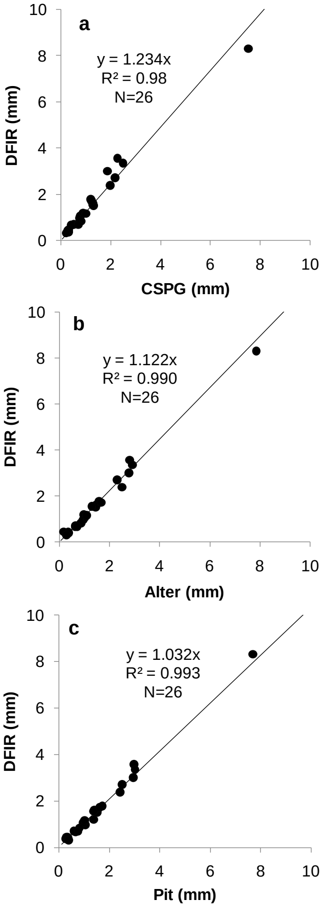

Figure 5. Scatter plots of snowfall for **(a)** the CSPG, **(b)** the Alter and **(c)** the Pit vs. the DFIR from September 2012 to September 2014.

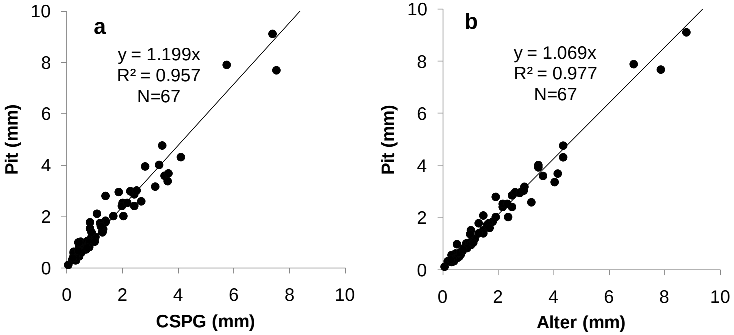

Figure 6. Scatter plots of snowfall for **(a)** the CSPG, and **(b)** the Alter vs. the Pit from September 2010 to September 2014.

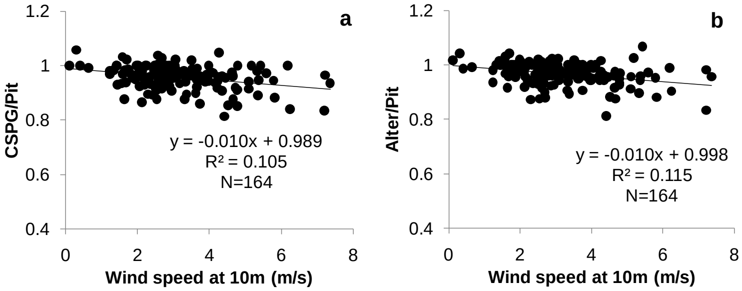

Figure 7. CRs of **(a)** CSPG/Pit and **(b)** Alter/Pit vs. wind speed at 10 m for Pit rainfall > 3 mm.

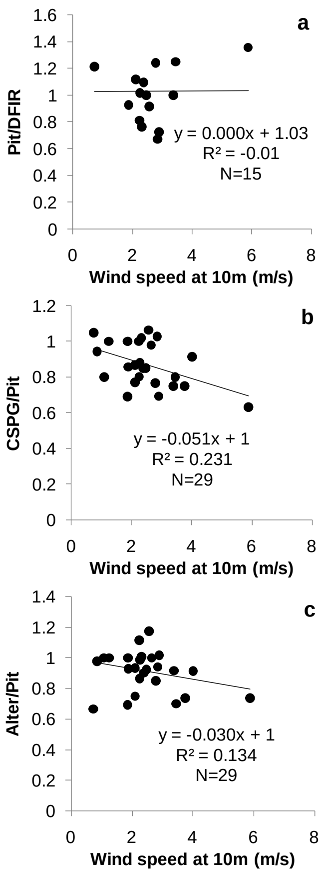

Figure 8. CRs of **(a)** Pit/DFIR, **(b)** CSPG/Pit and **(c)** Alter/Pit vs. wind speed at 10 m for Pit mixed precipitation > 1 mm.

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Precipitation measurement intercomparison in the Qilian Mountains

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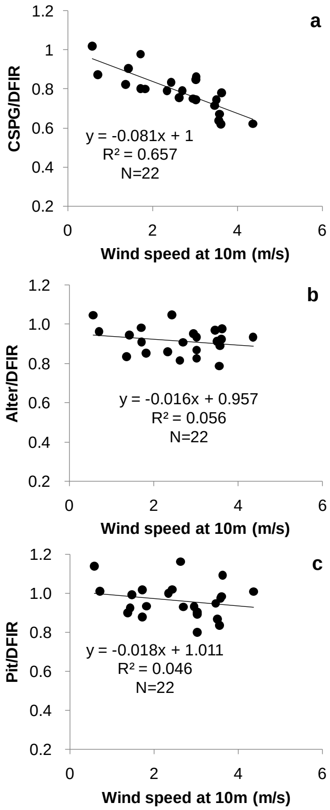

Figure 9. CRs of **(a)** CSPG/DFIR, **(b)** Alter/DFIR and **(c)** Pit/DFIR vs. wind speed at 10 m for DFIR snowfall > 1 mm.

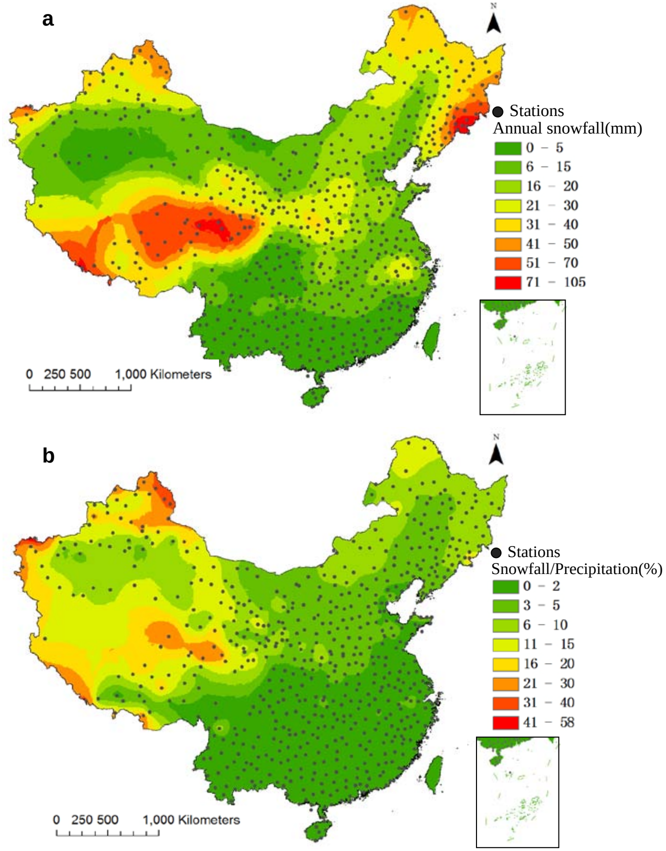

Figure 10. (a) Annual snowfall (mm) and **(b)** snowfall proportion (annual snowfall/annual precipitation) in China.

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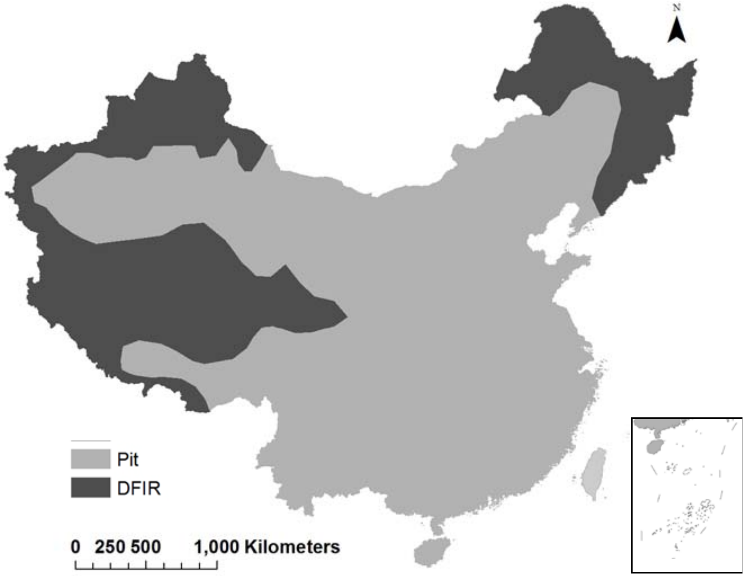

Figure 11. Applicable regions for the Pit and the DFIR as reference gauges in China.