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 the wind-induced error of Chinese standard precipitation gauge (CSPG) has not been well tested. An intercomparison experiment was carried out from September 2010 to April 2015 in the Hulu watershed, northeastern Tibet Plateau. Precipitation gauges included (1) an unshielded CSPG ($CSPG_{UN}$), (2) single Alter shield around a CSPG ($CSPG_{SA}$), (3) a CSPG in a pit ($CSPG_{PIT}$) and (4) a Double-Fence International Reference shield with a Tretyakov-shielded CSPG ($CSPG_{DFIR}$). The intercomparison experiments show that the $CSPG_{SA}$, $CSPG_{PIT}$, $CSPG_{DIFR}$ caught 0.9%, 4.5% and 3.4% more rainfall, 7.7%, 15.6% and 14.2% more mixed precipitation (snow with rain, rain with snow), 11.1%, 16.0% and 20.6% more snowfall, and 2.0%, 6.0% and 5.3% more precipitation (all types) than the $CSPG_{UN}$ from September 2012 to April 2015, respectively. The $CSPG_{PIT}$ and the $CSPG_{DFIR}$ caught more 3.6% and 2.5% rainfall, 7.3% and 6.0% more mixed precipitation, 4.4% and 8.5% more snowfall, and 3.9% and 3.2% more total precipitation than the $CSPG_{SA}$, respectively. Whereas the $CSPG_{DFIR}$ caught 1.0% less rainfall, 1.2% less mixed precipitation, 3.9% more snowfall and 0.6% less total precipitation than the $CSPG_{PIT}$, respectively. From most to least rain and mixed precipitation, the measurements are ranked as follows: $CSPG_{PIT}$ > $CSPG_{DFIR}$ > $CSPG_{SA}$ > $CSPG_{UN}$. For the snowfall, it follows as: $CSPG_{DFIR}$ > $CSPG_{PIT}$ > $CSPG_{SA}$ > $CSPG_{UN}$. The $CSPG_{DFIR}$ is used as reference to calculate the catch ratios (CRs) of the $CSPG_{UN}$, $CSPG_{SA}$ and $CSPG_{PIT}$. CR vs. 10m wind speed during the period of precipitation indicates that with increasing wind speed from 0 to 8.0m/s, the rainfall $CR_{UN/DFIR}$ or $CR_{SA/DFIR}$ decreased slightly. For the mixed precipitation, wind speed has no significant effect on $CR_{UN/DFIR}$ or $CR_{SA/DFIR}$ below 3.5m/s. For the snowfall, the $CR_{UN/DFIR}$ or $CR_{SA/DFIR}$ vs. wind speed shows that CR decreases with increasing wind speed. The adjustment equations for three different precipitation types for the $CSPG_{UN}$ and $CSPG_{SA}$ were established based on the CR vs. wind speed analysis and World Meteorological Organization (WMO) recommended procedure. They would help to improve the current bias error-adjusted

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method and precipitation accuracy in China. Results indicate that combined use of the $CSPG_{DFIR}$ and the $CSPG_{PIT}$ as reference gauges for snowfall and rainfall, respectively, could enhance precipitation observation precision. Applicable regions for the $CSPG_{PIT}$ or the $CSPG_{DFIR}$ as representative gauges for all precipitation types are present in China.

Keywords: Precipitation, Gauge catch ratio, Wind-induced undercatch, Field observation, Tibetan Plateau

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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). These errors affect the available water evaluation in a large number of economic and environmental applications (Tian et al., 2007; Ye et al., 2012).

Back in 1955, the World Meteorological Organization (WMO) conducted the first precipitation measurement intercomparison (Rodda, 1973). Its reference is a Mk2 gauge elevated 1 m above the ground and equipped with the Alter wind shield. But this reference does not show the correct amount of precipitation. This could be why the first international intercomparison failed (Struzer, 1971). Rodda (1967) compared the catch of a UK 5″ manual gauge exposed normally at the standard height of 30.5 cm above ground, with a Koschmieder-type gauge exposed in a pit. This gauge in a pit caught 6% more precipitation than the normally exposed gauge. In the second WMO precipitation measurement intercomparison (Rain, 1972–1976), the pit with anti-splash grid was designated the reference standard shield for rain gauges (Sevruk and Hamon,1984). In the third WMO precipitation measurement intercomparison (Snow, 1986–1993), the Double Fence International Reference (DFIR) shield with a Tretyakov shield was designated the reference standard snow gauges configuration (Goodison et al., 1998). In the fourth WMO precipitation measurement intercomparison (Rain Intensity, 2004–2008), different principles were tested to measure rainfall intensity and define a standardized adjustment procedure (Lanza et al., 2005). Because automation of precipitation measurements are widespread, the WMO Commission for Instruments and Methods of Observation (CIMO) organized the WMO Solid Precipitation Intercomparison Experiment (WMO-SPICE; Wolff et al., 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 still selected DFIR shield as part of the reference configurations.

The DFIR shield has been operated as part of reference configurations at 25 stations in 13 countries around the world (Golubev, 1985; Sevruk et al., 2009), but deviations from the DFIR measurements vary by gauge type and precipitation type (Goodison et al., 1998). In China, the Chinese standard precipitation gauge (CSPG) and the Hellmann gauge were firstly compared by using DFIR shield as reference configurations in the valley site of Tianshan (43°7′ N, 86°49′ E, 3720 m), during the third WMO precipitation measurement intercomparison experiment from 1987 to 1992 (Yang, 1988; Yang et al., 1991). The wetting, evaporation losses and trace precipitation of CSPG were well quantified based on the huge observation data. Because there are not wind data at the intercomparison site (Yang et al., 1991; Goodison et al., 1998), for the wind-induced undercatch, the derived CSPG catch ratio equations were based on the 10 m height wind speed at the open Daxigou Meteorological Station (43.06°, 86.5°E, 3540 m; Yang, 1988; Yang et al., 1991). The distance is about 1.7 km between the Daxigou site and the Tianshan valley site thus their wind speeds are different, inducing uncertainty in the catch ratio equations established by Yang et al. (1991) for the CSPG. During the period from 1992 to 1998, Ren and Li (2007) had conducted an intercomparison experiment at 30 sites (altitude varies from about 4.8 m to 3837 m) over China, and they used the pit as reference shield. A total of 29,000 precipitation events had been observed. However, the DFIR was not used as reference configurations, and there were only 3 stations located in the West Cold Regions of China (Chen et al., 2006) where the solid precipitation often occurred. Blowing snow and thick snow cover have traditionally limited the pit's use as a reference shield for snowfall and mixed precipitation (snow with rain, rain with snow). Ye et al. (2004, 2007) developed a bias-error adjusting method based on the observed data from 1987 to 1992 at the Tianshan valley site, and they found a new precipitation trend according to the adjusted precipitation data over the past 50 years in China (Ding et al., 2007). The new adjusted precipitation would change the knowledge on water balance in many basins in China (Tian et al., 2007; Ye et al., 2012). Although adjustment procedures and reference measurements were developed in several WMO international precipitation measurement intercomparisons (Goodison et al., 1998; Sevruk et al., 2009; Yang, 2014), and several bias-error adjusting methods had been put forward for the CSPG (Ye et al., 2004, 2007), the wind-induced error of CSPG had not been well tested especially in the cold and high regions such as the Tibetan Plateau, China. In these cold regions, solid precipitation often occurs and additional attention must be paid to wind-induced errors of gauge measured precipitation. Because of the limited intercomparison observation data in China, Ma et al. (2014) used the adjusted equations from neighboring countries except for the results from Tianshan China (Yang et al., 1991) to correct the wind-induced errors on Tibetan Plateau. However, their precipitation gauges are Tretyakov, MK2, Nepal2003, Indian and U.S. 8″ in the neighboring countries. As the third pole in the world, the Tibetan Plateau is an ecologically fragile region and the source of several large rivers in China and neighboring countries, accurate precipitation data are urgently needed. Therefore, we present a nearly five-year intercomparison experiment in the Qilian mountains at the northeastern Tibet Plateau, China, to establish adjustment equations for the widely used unshielded CSPGs.

The CSPG is the standard manual precipitation gauge used by the China Meteorological Administration (CMA) at more than 700 stations since the 1950s. These precipitation data sets have been used widely and need to be adjusted by using better methods. The Single Alter shield (SA) (Struzer, 1971) is used by the CMA to enhance catch ratios of automatic gauges (Yang, 2014), so the SA shield was selected as another intercomparison configuration for the present study. The $CSPG_{DFIR}$ was selected as the reference for all precipitation types. The intercomparison experiments tested and assessed existing bias adjustment procedures for the $CSPG_{UN}$ and the SA shield around a CSPG ($CSPG_{SA}$).

2 Data and Methods

2.1 Intercomparison experiments and relevant data

Precipitation intercomparison experiments (Fig.1, Table 1) were conducted at a grassland site in the Hulu watershed in the Qilian mountains, on the northeastern edge of Tibet Plateau, China (99°52.9′, 38°16.1′, 2980 m). A meteorological cryosphere-hydrology observation system (Chen et al., 2014a) has been established since 2008 in the Hulu watershed. Annual precipitation is about 447.2 mm during 2010-2012 and is concentrated during the warm season from May to September at this site. The annual temperature is approximately 0.4 °C, with a July mean (T_{mean}) of 4.2 °C and a January mean of -4.1°C (Table 1). The annual evaporation ability (E_0) is about 1102 mm (Table 1).

The intercomparison experiments included (1) an unshielded CSPG ($CSPG_{UN}$; orifice diameter=20 cm, height=70 cm), (2) single Alter shield around a CSPG ($CSPG_{SA}$), (3) a CSPG in a pit ($CSPG_{PIT}$), and (4) a DFIR shield with a Tretyakov-shielded CSPG ($CSPG_{DFIR}$) (Fig.1, Table 2). The $CSPG_{UN}$, $CSPG_{SA}$ and $CSPG_{PIT}$ were installed before September 2010, whereas the $CSPG_{DFIR}$ was installed in September 2012 (Table 2). In the cold season (October to April), snowfall dominated the precipitation events, and in the 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) according to the CMA's criterion (CMA, 2007a). In the warm season, P is measured by volume. 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. If there is frost on the outside surface of the collector, it will be wiped up by using a dry hand towel. In the rare cases of snowfall accumulating on the rim of the collector, half of them (semi circular) will be removed before they are weighted.

The precipitation phase (snow, rain and mixed) is discriminated by observer according to the CMA's criterion (CMA, 2007b). This method has been used since the 1950s at the more than 700 stations in China. Based on the CSPG measurements, several methods of phase discrimination have been reported, such as the air temperature index method (e.g. Zhang et al., 2004; Ye et al., 2004; Chen et al., 2014b), dew point index method (e.g. Chen et al., 2014b), and the new wet bulb temperature index method (Ding et al., 2014). However, the parameters of these methods vary largely in spatial, and their reference precipitation phase data are still from the CMA's stations.

Relevant variables such as air temperature (maximum and minimum; T_{max} and T_{min}) 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 1.5m and 2.5m heights in association with relative humidity (HMP45D, Vaisala) and precipitation (Chen et al., 2014). They are observed every 30 seconds and are saved as half-hourly values (sum or mean). The specific meteorological conditions at the site are summarized in Table 1.

Fig.1 about here

Table 1 and Table 2 about here

2.2 Adjustment methods

This field experiment focuses on two key aspects. One is comparisons among the $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$. Another purpose is to establish adjustment equations for the $CSPG_{UN}$ and the $CSPG_{SA}$ by using the $CSPG_{DFIR}$ as reference. To adjust 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 adjusted precipitation, K is the wind-induced coefficient and P_g is the gauge-measured precipitation. P_w is the wetting loss, P_e is the evaporation loss, P_t is trace precipitation and P_{DFIR} is DFIR-shielding precipitation. For the CSPG, P_w is 0.23 mm for rainfall measurements, 0.30 mm for snow and 0.29 mm for mixed precipitation (Yang, 1988; Yang et al., 1991), according to the measurements in the Tianshan valley site. Ren and Li (2007) reported the mean P_w was about 0.19 mm for the total precipitation over eastern China. The CSPG design reduces P_e to a near-zero value smaller than other losses in the warm, rainy season (Ye et al., 2004; Ren and Li, 2007). In winter, P_e is already small (0.10–0.20 mm/day) according to the results in Finland (Aaltonen et al., 1993) and Mongolia (Zhang et al., 2004). To prevent evaporation loss in Chinese operational observations on some particular days, e.g., hot and dry days or days of snow, precipitation is measured as soon as the precipitation event stops (CMA, 2007a; Ren and Li, 2007). A precipitation event of less than 0.10 mm is beyond the resolution of the CSPG 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 trace observations per day.

In this field experiment, the $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ have same P_w, P_e and P_t that have been well quantified as described above. Thus the focus of the present study is the wind-induced error. Wind may be the most important factor influencing precipitation measurement in high mountain conditions.

The WMO has given Eqs.(2)-(4) for the shielded Tretyakov gauge catch ratio versus 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). Therefore, in this paper, the catch ratio (CR, %) follows their definition by using $CSPG_{DFIR}$ as reference.

$$CR_{snow} = 103.1 - 8.67W_s + 0.3T_{\max} \quad (2)$$
$$CR_{mix} = 96.99 - 4.46W_s + 0.88T_{\max} + 0.22T_{\min} \quad (3)$$
$$CR_{rain} = 100.0 - 4.77W_s^{0.56} \quad (4)$$

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 (m s^{-1}); $T_{\max}$ and $T_{\min}$ are daily maximum and minimum air temperatures (^{o}C).

The CMA stations usually observe wind speeds at 10 m height, so Yang et al. (1991) have given Eqs.(5)-(7) for CSPG catch ratios versus daily mean wind speed W_s (m s^{-1}) at 10 m height. These equations are based on the huge precipitation gauge intercomparison experiment data at the Tianshan valley site and wind speed data at the Daxigou station:

$$CR_{snow} = 100\exp(-0.056W_{s10}) \qquad (0 < W_s < 6.2) \qquad (5)$$
$$CR_{rain} = 100\exp(-0.04W_{s10}) \qquad (0 < W_s < 7.3) \qquad (6)$$
$$CR_{mix} = CR_{snow} - (CR_{snow} - CR_{rain})(T_{mean} + 2)/4 \qquad (7)$$

where T_{mean} is the daily mean air temperature (^{o}C).

In this paper, two types of equations are established. One is for easy application by using 10m-height wind speed during the period of precipitation in China. They are similar to and revisions of the Eqs.(5)-(7). Another type is similar to Eqs.(2)-(4), which use daily mean wind speed at gauge height. For CSPG, the gauge height is 70 cm (Table 2).

Wind speeds at gauge height ($W_{s0.7}$) and 10 m height (W_{s10}) were calculated by using half-hourly wind speed data at 1.5 m ($W_{s1.5}$) and 2.5 m heights ($W_{s2.5}$), according to the Monin-Obukhov theory and the gradient method (Bagnold,1941; Dyer and Bradley, 1982):

$$W_{sZ} = \frac{\ln Z - \ln Z_0}{\ln 1.5 - \ln Z_0} W_{s1.5} \quad (8)$$

$$\ln Z_0 = \frac{W_{s2.5} \ln 1.5 - W_{s1.5} \ln 2.5}{W_{s2.5} - W_{s1.5}} \quad (9)$$

Where *Z* is 0.7 m or 10 m.

3 Results

From September 2010 to April 2015, a total of 608 precipitation events were recorded at the intercomparison site for $CSPG_{UN}$, $CSPG_{SA}$ and $CSPG_{PIT}$, respectively (Table 3). Snow occurred 84 times, mixed precipitation occurred 44 times, and rain occurred 480 times during this period. From September 2012 to April 2015, a subset of 283 precipitation events were recorded for the $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$, and $CSPG_{DFIR}$ gauges, respectively (Table 3). During this period, snow occurred 43 times, mixed precipitation occurred 29 times, and rainfall occurred 211times.

Table 3 about here

3.1 Precipitation gauge intercomparison for rainfall

Good linear correlations are found among the four CSPG installments (Fig.2). From September 2010 to April 2015, the $CSPG_{PIT}$ caught 4.7% and 3.4% more rainfall than the $CSPG_{UN}$ and the $CSPG_{SA}$ respectively (($CSPG_{PIT}$-$CSPG_{UN}$)/$CSPG_{UN}$*100; similarly hereinafter). The $CSPG_{SA}$ caught 1.3% more rainfall than the $CSPG_{UN}$ (Table 3).

During the period from September 2012 to April 2015, the $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DIFR}$ caught 0.9%, 4.5% and 3.4% more rainfall than $CSPG_{UN}$, respectively. The $CSPG_{PIT}$ and the $CSPG_{DFIR}$ caught more 3.6% and 2.5% rainfall than the $CSPG_{SA}$, respectively. Whereas the $CSPG_{DFIR}$ caught 1.0% less rainfall than the $CSPG_{PIT}$ (Table 3, Fig.2). Comparative studies indicate that $CSPG_{PIT}$ catches more rainfall and total *P* than the $CSPG_{DFIR}$ or the other gauges at the experiment site (Table 3, Fig.2).

Fig.2 about here

3.2 Precipitation gauge intercomparison for mixed precipitation

From September 2010 to April 2015, a total of 44 mixed precipitation events were observed. The $CSPG_{PIT}$ caught 12.1% and 5.6% more mixed *P* than the $CSPG_{UN}$ and the $CSPG_{SA}$, respectively. The $CSPG_{SA}$ caught 6.1%

more mixed *P* than the $CSPG_{UN}$ (Table 3). From September 2012 to April 2015, the $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DIFR}$ caught 7.7%, 15.6% and 14.2% more mixed *P* than the $CSPG_{UN}$, respectively. The $CSPG_{PIT}$ and the $CSPG_{DFIR}$ caught more 7.3% and 6.0% mixed *P* than the $CSPG_{SA}$, respectively. Whereas the $CSPG_{DFIR}$ caught 1.2% less mixed *P* than the $CSPG_{PIT}$ (Table 3).

Good linear correlations are observed among the gauges (Fig.3). The $CSPG_{PIT}$ caught 1.1 mm more mixed precipitation than the $CSPG_{DFIR}$ in the near three successive years. The linear relationship is statistically significant with an R^2 value as about 0.98 (Fig.3f). Thus the $CSPG_{PIT}$ instead of the $CSPG_{DFIR}$ could be selected as the reference gauge for the $CSPG_{UN}$ and the $CSPG_{SA}$ at the experimental site.

Fig.3 about here

3.3 Precipitation gauge intercomparison for snowfall

From September 2010 to April 2015, a total of 84 snowfall events are observed. The $CSPG_{PIT}$ caught 21.0% and 6.4% more snowfall than the $CSPG_{UN}$ and the $CSPG_{SA}$ respectively. The $CSPG_{SA}$ caught 13.7% more snowfall than the $CSPG_{UN}$ (Table 3). From September 2012 to April 2015, the $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DIFR}$ caught 11.1%, 16.0% and 20.6% more snowfall than the $CSPG_{UN}$, respectively. The $CSPG_{PIT}$ and the $CSPG_{DFIR}$ caught more 4.4% and 8.5% snowfall than the $CSPG_{SA}$, respectively (Table 3).

Good linear correlations are also observed between the $CSPG_{DFIR}$ and each of the other three gauges (Fig.4). From Fig.4f, there is a linear correlation existed between the $CSPG_{PIT}$ and the $CSPG_{DFIR}$ ($CSPG_{DFIR}$=1.029$CSPG_{PIT}$, R^2=0.994). Although the $CSPG_{DFIR}$ caught 3.9% more snowfall than the $CSPG_{PIT}$ (Table 3), the difference of total snowfall (43 events) between the $CSPG_{DFIR}$ and the $CSPG_{PIT}$ was only about 3.4 mm (Table 3). This suggests that the $CSPG_{PIT}$ could be used as the reference gauge for snow precipitation events at the experiment site.

Fig.4 about here

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). As described above, the wind-induced error of CSPG measurement has not been well tested. Because the CMA stations observe wind speeds at 10 m height, so the $CSPG_{UN}$ and the $CSPG_{SA}$ adjustment equations for single precipitation event are established with 10 m height wind speeds during the period of precipitation. On daily scale, the adjustment equations similar to Eqs.(2)-(4) are also established, based on the daily mean wind speed data at gauge height (for the CSPG, it is 0.7m.) and air temperature data.

To minimize ratio scatter of among different gauges, precipitation events greater than 3.0 mm are normally selected in the ratio vs. wind analysis (Yang et al. 1995; Yang et al., 2014). In the Hulu watershed, most snowfall and mixed precipitation events are less than 3.0 mm. For this reason, single or daily snowfall and mixed precipitation greater than 1.0 mm was chosen to use in this chapter. Whereas for the rainfall, precipitation greater than 3.0 mm was selected. The numbers of the chosen precipitation events are shown in Table 4. The catch ratio vs. wind speed relations of different precipitation types are summarized in Table 4 too. As shown in Table 4, all the $CR_{PIT/DFIR}$ vs. $W_{s0.7}$ or W_{s10} relations do not pass the F-test when α=0.10. Therefore, only $CR_{UN/DFIR}$ and $CR_{SA/DFIR}$ vs. wind speed relations are discussed in the following text.

Table 4 about here

3.4.1 Rainfall catch ratio vs. wind speed

Fig.5 presents scatter plots of the $CR_{UN/DFIR}$ or $CR_{SA/DFIR}$ vs. wind speed. The CRs vary from 80% to 110%. With increasing wind speed, the CRs decreased slightly. The following two equations (10) and (11) could be used to adjust the rainfall event data from the $CSPG_{UN}$ and $CSPG_{SA}$, respectively. They both pass the F-test when $\alpha<0.1$ (Table 4).

$$CR_{UN/DFIR,Rain} = 0.181W_{s10}^3 - 2.028W_{s10}^2 + 5.983W_{s10} + 92.24 \qquad 0<W_{s10}<7.4 \qquad (10)$$

$$CR_{SA/DFIR,Rain} = 0.188W_{s10}^3 - 2.027W_{s10}^2 + 5.554W_{s10} + 94.27 \qquad 0<W_{s10}<7.4 \qquad (11)$$

Where $CR_{UN/DFIR,Rain}$ and $CR_{SA/DFIR,Rain}$ is the rainfall catch ratio (%) of the $CSPG_{UN}$ and the $CSPG_{SA}$, respectively, W_{s10} is the wind speed at 10m height during the period of rainfall (m s^{-1}).

Fig.5 about here

On daily scale, the best relationships between rainfall CRs and wind speed at gauge height ($W_{s0.7}$) are also the 3rd order, but they don't pass the F-test even α=0.25 (Table 4).

3.4.2 Mixed precipitation catch ratio vs. wind speed

For the mixed precipitation events, the $CR_{UN/DFIR,Mixed}$ and $CR_{SA/DFIR,Mixed}$ vs. W_{s10} relations are exponential (Table 4, Fig.6). The CRs vary largely from about 60% to 120%. For the $CSPG_{UN}$, the exponential relationship Eq.(12) passes the F-test when $\alpha<0.10$, whereas for the $CSPG_{SA}$, the Eq.(13) doesn't pass but has a α value of about 0.16 (Table 4).

Fig.6 about here

$$CR_{UN/DFIR,Mixed} = 102.9e^{-0.07W_{s10}} \qquad 0<W_{s10}<5.9 \qquad (12)$$

$$CR_{SA/DFIR,Mixed} = 102.4e^{-0.05W_{s10}} \qquad 0<W_{s10}<5.9 \qquad (13)$$

On daily scale, the best relationships between mixed precipitation CRs and wind speed at gauge height ($W_{s0.7}$) are power law expressions (Table 4, Fig.6). Similarly, for the $CSPG_{UN}$, the Eq. (14) passes the F-test when $\alpha<0.10$, whereas the Eq.(15) doesn't with a α value of about 0.12 (Table 4).

$$CR_{UN/DFIR,Mixed} = 88.49W_{s0.7}^{-0.20} \qquad 0<W_{s0.7}<2.9 \qquad (14)$$

$$CR_{SA/DFIR,Mixed} = 93.64W_{s0.7}^{-0.12} \qquad 0<W_{s0.7}<2.9 \qquad (15)$$

From Eq. (3), air temperature may also affect the mixed precipitation CRs on daily scale. Eqs. (16)-(17) are established as follows. However, these two new equations don't pass the F-test when α=0.20.

$$CR_{UN/DFIR,Mixed} = 13.83W_{s0.7}^{-4.91} + 1.25T_{\max} - 0.88T_{\min} + 62.21 \qquad \alpha=0.20 \qquad (16)$$

$$CR_{SA/DFIR,Mixed} = 10.74W_{s0.7}^{-4.74} + 0.85T_{\max} - 0.18T_{\min} + 76.20 \qquad \alpha=0.29 \qquad (17)$$

Where $T_{\max}$ and $T_{\min}$ is the daily maximum and minimum air temperature (^{o}C), respectively.

3.4.3 Snowfall catch ratio vs. wind speed

For the snowfall events, the $CR_{UN/DFIR,Snow}$ and the $CR_{SA/DFIR,Snow}$ vs. W_{s10} relations are evident (Table 4, Fig.7). For the $CSPG_{UN}$, the exponential relationship Eq.(18) passes the F-test when $\alpha<0.001$. The Eq.(18) is similar with the Eq.(5) suggested by Yang et al. (1991). For the $CSPG_{SA}$, the power law expression Eq.(19) passes the F-test when $\alpha<0.05$ (Table 4).

Fig.7 about here

$$CR_{UN/DFIR,Snow} = 103.5e^{-0.09W_{s10}} \qquad 0<W_{s10}<4.8 \qquad (18)$$

$$CR_{SA/DFIR,Snow} = 97.35W_{s10}^{-0.05} \qquad 0<W_{s10}<4.8 \qquad (19)$$

On daily scale, for the $CSPG_{UN}$ and the $CSPG_{SA}$, the Eq. (20) and Eq. (21) pass the F-test when $\alpha<0.001$ and $\alpha<0.10$, respectively (Table 4). Eqs. (18) - (21) could be directly used to calibrate the wind-induced snowfall measurement errors for $CSPG_{UN}$ and the $CSPG_{SA}$.

$$CR_{UN/DFIR,Snow} = 96.28 W_{s0.7}^{-0.32} \qquad 0<W_{s0.7}<3.1 \qquad (20)$$

$$CR_{SA/DFIR,Snow} = -8.01\ln(W_{s0.7}) + 97.61 \qquad 0<W_{s0.7}<3.1 \qquad (21)$$

Air temperature may also affect the snowfall CRs on daily scale as shown in Eq.(2). Eqs. (22)-(23) are the new equations associating with daily maximum air temperature. However, these two new equations are not better than Eqs. (20)-(21) according to their α value of F-test.

$$CR_{UN/DFIR,Snow} = 42.29 W_{s0.7}^{-1.06} - 1.06 T_{\max} + 55.91 \qquad \alpha=4.2E\text{-}5 \qquad (22)$$

$$CR_{SA/DFIR,Snow} = -9.46\ln(W_{s0.7}) - 0.31 T_{\max} + 98.76 \qquad \alpha=0.17 \qquad (23)$$

4 Discussion

4.1 Comparison with other studies

Yang et al. (1991) carried out a precipitation intercomparison experiment from 1987 to 1992 in the valley site of Tianshan. Their results indicated that the ratios of $CSPG_{DFIR}/CSPG_{UN}$ for snowfall and mixed precipitation were 1.222 and 1.160, respectively. In the Hulu watershed, the ratios of $CSPG_{DFIR}/CSPG_{UN}$ for snowfall and mixed precipitation were 1.165 (Fig.4c) and 1.072 (Fig.3c), and the ratios of $CSPG_{PIT}/CSPG_{UN}$ for snowfall and mixed precipitation were 1.162 (Fig.4b) and 1.082 (Fig.3b), 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 (W_{s10}) on rainfall or snowfall days never exceeds 6 m s^{-1} and 88% of the yearly total precipitation took place with wind speeds below 3 m s^{-1}. For the Hulu watershed site, daily mean wind speeds ($W_{s0.7}$) on precipitation days never exceeded 3.5 m s^{-1}, and over 98.9% of the precipitation events occurred when daily mean wind speeds were below 3 m s^{-1}. During the period of precipitation, the largest wind speed at 10 m height is about 8.8 m s^{-1}, and over 54.2% of the precipitation events occurred when wind speeds were below 3 m s^{-1}.

As Ren et al. (2003) reported, among 30 comparison stations in China, the $CSPG_{PIT}$ caught 3.2% (1.1~7.9%) more rainfall and 11.0% (2.2~24.8%) more snowfall than the $CSPG_{UN}$. Large wind-induced differences are often observed at the western mountainous stations and in the Northeastern China. At the Gangcha station (100°08′, 37°20′, 3015 m) which also lies in the Qilian Mountains with similar elevations with and about 200 km far from the Hulu watershed site, the $CSPG_{PIT}$ caught 7.9% more rainfall and 16.8% more snowfall than the $CSPG_{UN}$ from 1992 to 1998. In our study, the $CSPG_{PIT}$ got 4.7% more rainfall, 21.0% more snowfall, and 12.1% more mixed precipitation than the $CSPG_{UN}$ from September 2010 to April 2015 (Table 3). The outcome presented in this study is somewhat different from the Ren et al. (2003) presented due to the different wind regime.

4.2 Possibility of the $CSPG_{PIT}$ as a reference for solid precipitation

The pit shield is the WMO reference configuration for liquid precipitation measurements and the DFIR is the reference configuration for solid precipitation measurements (Sevruk et al., 2009). In this study, the $CSPG_{PIT}$ measures more rainfall and mixed precipitation than the $CSPG_{DFIR}$. For the snowfall, the catch ratio for the $CSPG_{PIT}$ is 0.96, close to the $CSPG_{DFIR}$ catch ratio. The difference of total snowfall (43 events) between the $CSPG_{PIT}$ and the $CSPG_{DFIR}$ is only about 3.4 mm from September 2012 to April 2015 at the Hulu watershed site. Thus the $CSPG_{PIT}$ could serve as a reference for liquid and solid precipitation in the environment similar to the Hulu watershed site. Considering the $CSPG_{PIT}$'s greater simplicity and practicality, it could be more convenient for researchers and observers to use the $CSPG_{PIT}$ as the standard reference for snow and mixed precipitation in other locations. Precipitation collected by the $CSPG_{PIT}$ would be most affected when blowing or drifting snow occurred, and induce a faulty precipitation value (Goodison et al., 1998; 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). Fig.8 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. Ren and Li (2007) has reported, among the 29276 precipitation events, there are only 784 blowing or drifting snow events accounting to about 2.7% at the 30 stations over China. These blowing or drifting snow events mostly occur in the south-eastern Tibetan Plateau, northern Xinjiang province and north-eastern China (Ren et al., 2003). The applicable regions for the $CSPG_{PIT}$ and the $CSPG_{DFIR}$ as reference gauges are shown in Fig.9 based on CMA snowfall and snow depth data.

Fig.8 about here

Fig.9 about here

4.3 Uncertainties of the experiment

Although the measurements procedure is based on the CMA's criterion, the manual observation has low frequency, and as a result, some precipitation events are summarized as one event especially in the evening. The automatic meteorological tower can observe half-hourly precipitation and wind speeds during the precipitation period, but the $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ are observed twice per day. In this field experiment, the precipitation phase is also discriminated by the observers. This method is somewhat rough though it has been the standard way since the 1950s at the CMA stations.

The used wind speeds at gauge height and at the 10 m height are not observed directly, but they are calculated from the observed data at 1.5 m and 2.5m heights according to the Monin-Obukhov theory and the gradient method (Eqs.(8)-(9)). Although this method is widely used, it is effective only under neutral atmospheric conditions. During the precipitation period from September 2012 to April 2015, Z_0 is about 0.06 m of the average but it varies from near zero to 0.67 m. As shown in Fig.10, about 68.9% and 95.1% of Z_0 is lower than 0.05 m and 0.25 m, respectively. In the occasional cases that Z_0 is very large, the Z_0 is arbitrarily assigned a value (1/2 of grass height at the site).

Fig. 10 about here

5 Conclusions

The precipitation intercomparsion experiment in the Hulu watershed indicates that the $CSPG_{PIT}$ catches more rainfall, mixed precipitation and total precipitation than the $CSPG_{DFIR}$. From most to the least rainfall and mixed precipitation, it can be ordered as follows: $CSPG_{PIT}$ > $CSPG_{DFIR}$ > $CSPG_{SA}$ > $CSPG_{UN}$. While in the snowy season, it follows the rule that better wind-shield catch with more snow, and they can be ordered: $CSPG_{DFIR}$ > $CSPG_{PIT}$ > $CSPG_{SA}$ > $CSPG_{UN}$. The wind-induced bias of $CSPG_{SA}$ and the $CSPG_{UN}$ are well tested, and the most adjustment equations could be used. They would help to improve the precipitation accuracy in China.

In the regions with little snowfall such as the south and central part of China, and the regions with similar climate and environment to the Hulu watershed site, the $CSPG_{PIT}$ could be used as the reference gauge considering its highest catch ratio, simplicity and low cost. In north-east China, northern Xinjiang province and southeastern Tibetan Plateau where snowfall often occurs, the best choice for reference gauge would be the $CSPG_{PIT}$ for rainfall and $CSPG_{DFIR}$ for snowfall observations.

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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
Monthly precipitation 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
Monthly mean air temperature T_{mean} (°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
Monthly mean daily maximum air temperature 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
Monthly mean daily minimum air temperature 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
Monthly mean wind speed at the 1.5m height $W_{s1.5}$ (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
Monthly mean wind speed at the 2.5m height $W_{s2.5}$ (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
Monthly evaporation ability 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
An unshielded China standard precipitation gauge (CMA, 2007a)	$CSPG_{UN}$	φ=20cm, h=70cm	Jun 2009	Apr, 2015	20:00 and 08:00, LT
Single Alter shield (Struzer, 1971) around a CSPG	$CSPG_{SA}$	φ=20cm, h=70cm	Jun 2009	Apr, 2015	20:00 and 08:00, LT
A CSPG in a Pit (Sevruk and Hamon, 1984)	$CSPG_{PIT}$	φ=20cm, h=0cm	Sep 2010	Apr, 2015	20:00 and 08:00, LT
DFIR shield(Goodison et al., 1998) around a CSPG	$CSPG_{DFIR}$	φ=20cm, h=3.0m	Sep 2012	Apr, 2015	20:00 and 08:00, LT

Table 3. Summary of precipitation observations at the Hulu watershed intercomparison site, 2010-2015.

Date	Phase	No. of events	Total precipitation and catch ratio (CR, %)													
			$CSPG_{UN}$ (mm)	CR	$100\left(\frac{CSPG_{SA}}{CSPG_{UN}}-1\right)$	$100\left(\frac{CSPG_{PIT}}{CSPG_{UN}}-1\right)$	$100\left(\frac{CSPG_{DFIR}}{CSPG_{UN}}-1\right)$	$CSPG_{SA}$ (mm)	CR	$100\left(\frac{CSPG_{PIT}}{CSPG_{SA}}-1\right)$	$100\left(\frac{CSPG_{DFIR}}{CSPG_{SA}}-1\right)$	$CSPG_{PIT}$ (mm)	CR	$100\left(\frac{CSPG_{DFIR}}{CSPG_{PIT}}-1\right)$	$CSPG_{DFIR}$ (mm)	CR
Sep 2010-Apr 2015	All	608	1986.8	93.9	2.6	6.5		2038.1	96.4	3.8		2115.1	100			
	rain	480	1700.7	95.5	1.3	4.7		1723.4	96.7	3.4		1781.4	100			
	mixed	44	139.9	89.2	6.1	12.1		148.5	94.7	5.6		156.8	100			
	snow	84	146.2	82.6	13.7	21.0		166.2	94.0	6.4		176.9	100			
Sep 2012-Apr 2015	All	283	1066.7	94.9	2.0	6.0	5.3	1088.4	96.9	3.9	3.2	1130.9	100.6	-0.6	1123.7	100
	rain	211	920.7	96.7	0.9	4.5	3.4	928.6	97.5	3.6	2.5	961.8	101.0	-1.0	952.2	100
	mixed	29	71.1	87.6	7.7	15.6	14.2	76.6	94.3	7.3	6.0	82.2	101.2	-1.2	81.2	100
	snow	43	74.9	82.9	11.1	16.0	20.6	83.2	92.1	4.4	8.5	86.9	96.2	3.9	90.3	100

Table 4. Catch ratio (CR) vs. wind speed relations at the Hulu watershed intercomparison site, 2012-2015.

Temporal scale	Phase	Gauges	Best catch ratio (CR) vs. wind speed relation*	*P* (mm)	No. of events	F-test
Precipitation event	Rain	$CSPG_{UN}$	$CR_{UN/DFIR,Rain}=0.181W_{s10}^3-2.028W_{s10}^2+5.983W_{s10}+92.24$ R^2=0.070	P>3.0	103	α=0.06
		$CSPG_{SA}$	$CR_{SA/DFIR,Rain}=0.188W_{s10}^3-2.027W_{s10}^2+5.554W_{s10}+94.27$ R^2=0.099			α=0.01
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Rain}=0.150W_{s10}^3-1.748W_{s10}^2+6.183W_{s10}+94.20$ R^2=0.023			α=0.50
	Mixed	$CSPG_{UN}$	$CR_{UN/DFIR,Mixed}=102.9e^{-0.07W_{s10}}$ R^2=0.198	P>1.0	24	α=0.07
		$CSPG_{SA}$	$CR_{SA/DFIR,Mixed}=102.4e^{-0.05W_{s10}}$ R^2=0.102			α=0.16
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Mixed}=-5.81\ln(W_{s10})+106.4$ R^2=0.023			α=0.47
	Snow	$CSPG_{UN}$	$CR_{UN/DFIR,Snow}=103.5e^{-0.09W_{s10}}$ R^2=0.420	P>1.0	32	α=4.7E-5
		$CSPG_{SA}$	$CR_{SA/DFIR,Snow}=97.35W_{s10}^{-0.05}$ R^2=0.122			α=0.04
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Snow}=0.160W_{s10}^3+0.956W_{s10}^2-9.754W_{s10}+109.9$ R^2=0.110			α=0.30
Daily precipitation	Rain	$CSPG_{UN}$	$CR_{UN/DFIR,Rain}=-1.400W_{s0.7}^3 9.403W_{s0.7}^2-18.22W_{s0.7}+106.8$ R^2=0.045	P>3.0	90	α=0.26
		$CSPG_{SA}$	$CR_{SA/DFIR,Rain}=-0.924W_{s0.7}^3+6.525W_{s0.7}^2-13.47W_{s0.7}+105.7$ R^2=0.031			α=0.43
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Rain}=-0.952W_{s0.7}^3+6.371W_{s0.7}^2-12.62W_{s0.7}+108.4$ R^2=0.017			α=0.68
	Mixed	$CSPG_{UN}$	$CR_{UN/DFIR,Mixed}=88.49W_{s0.7}^{-0.20}$ R^2=0.169	P>1.0	21	α=0.06
		$CSPG_{SA}$	$CR_{SA/DFIR,Mixed}=93.64W_{s0.7}^{-0.12}$ R^2=0.122			α=0.12
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Mixed}=101.6W_{s0.7}^{-0.05}$ R^2=0.017			α=0.60
	Snow	$CSPG_{UN}$	$CR_{UN/DFIR,Snow}=96.28W_{s0.7}^{-0.32}$ R^2=0.577	P>1.0	27	α=5.7E-6
		$CSPG_{SA}$	$CR_{SA/DFIR,Snow}=-8.01\ln(W_{s0.7})+97.61$ R^2=0.111			α=0.09
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Snow}=-5.760W_{s0.7}^3+41.641W_{s0.7}^2-93.05W_{s0.7}+160.5$ R^2=0.134			α=0.33

*: W_{s10}-Wind speed during period of precipitation at 10 m height; $W_{s0.7}$-Daily mean wind speed at gauge height (0.7 m for CSPG).

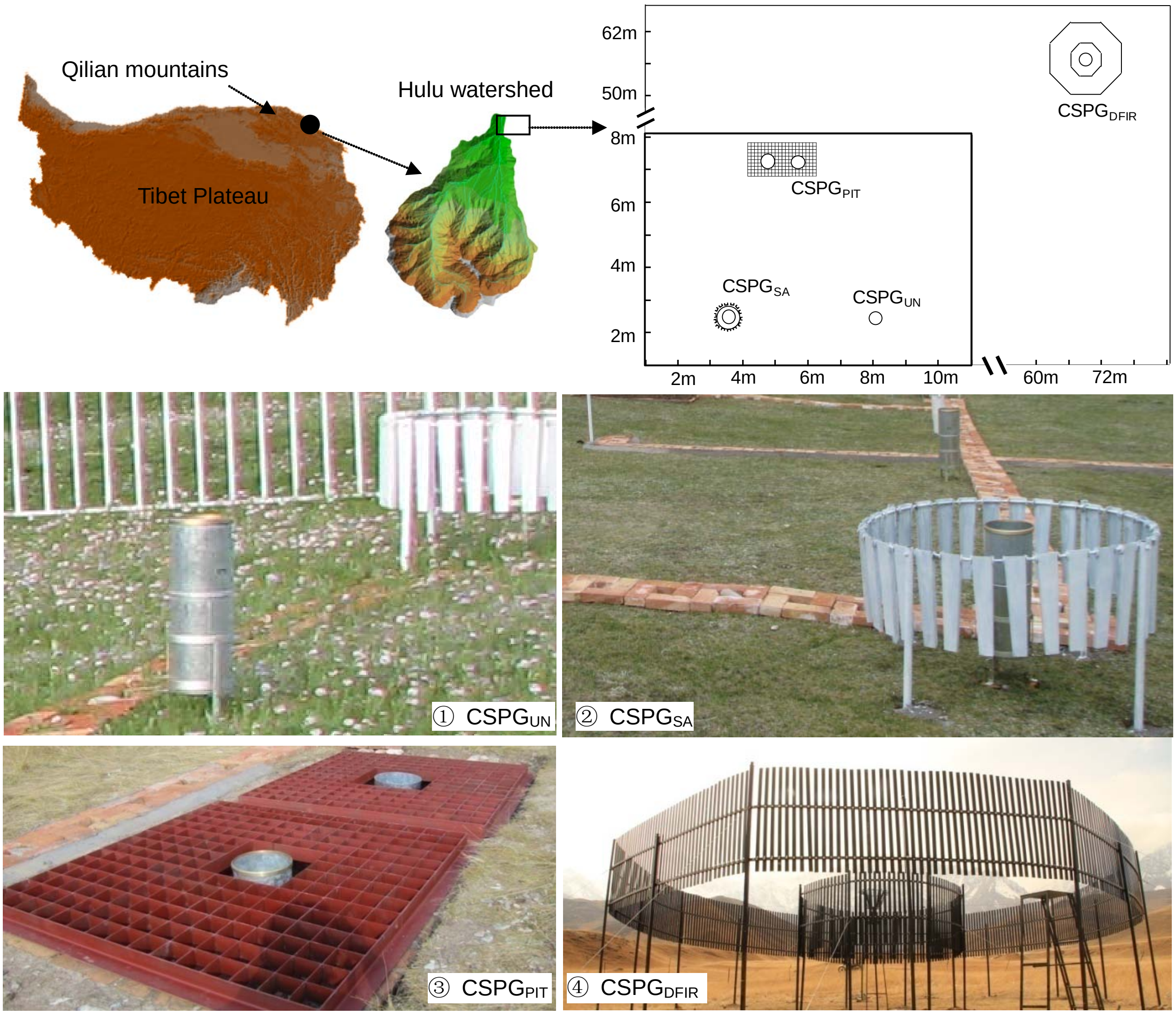

Figure 1. Precipitation gauge intercomparison experiment in the Qilian mountains, Tibetan Plateau.

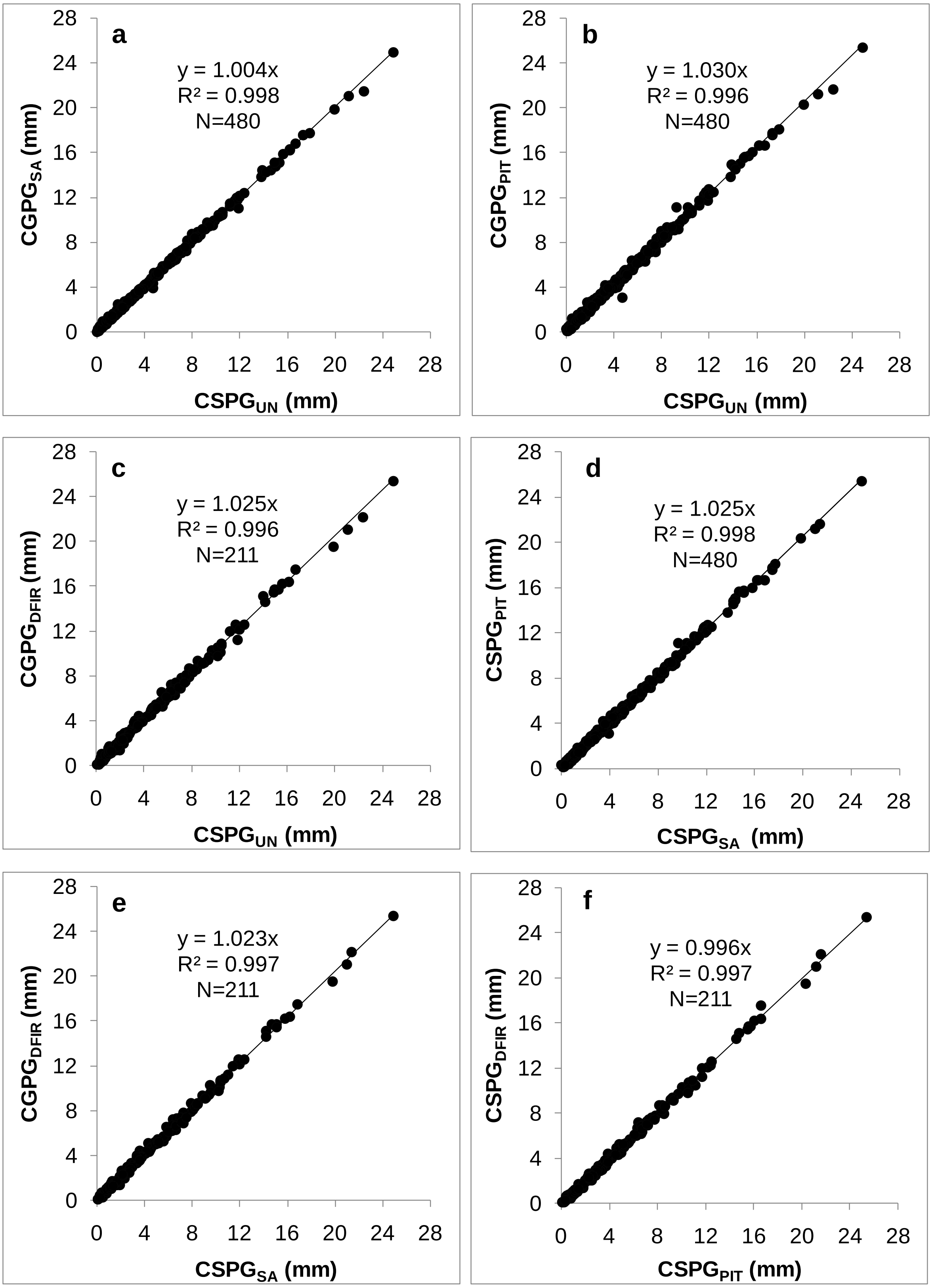

Figure 2. Intercomparison plots among $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ for the rainfall events from September 2010 (**a**, **b** and **d**) or September 2012 (**c**, **e** and **f**) to April 2015**.**

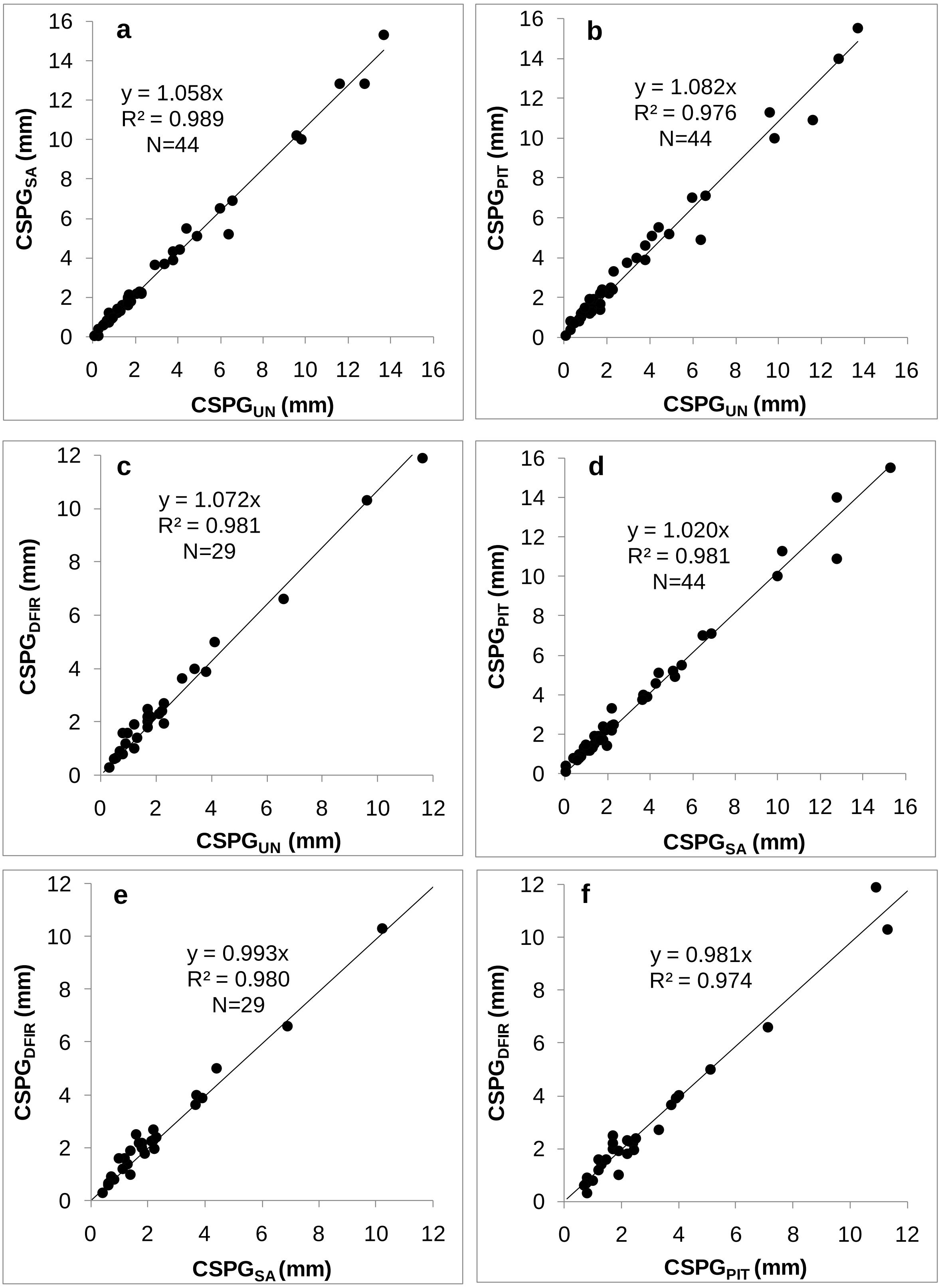

Figure 3. Intercomparison plots among $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ for the mixed precipitation events from September 2010 (**a**, **b** and **d**) or September 2012 (**c**, **e** and **f**) to April 2015**.**

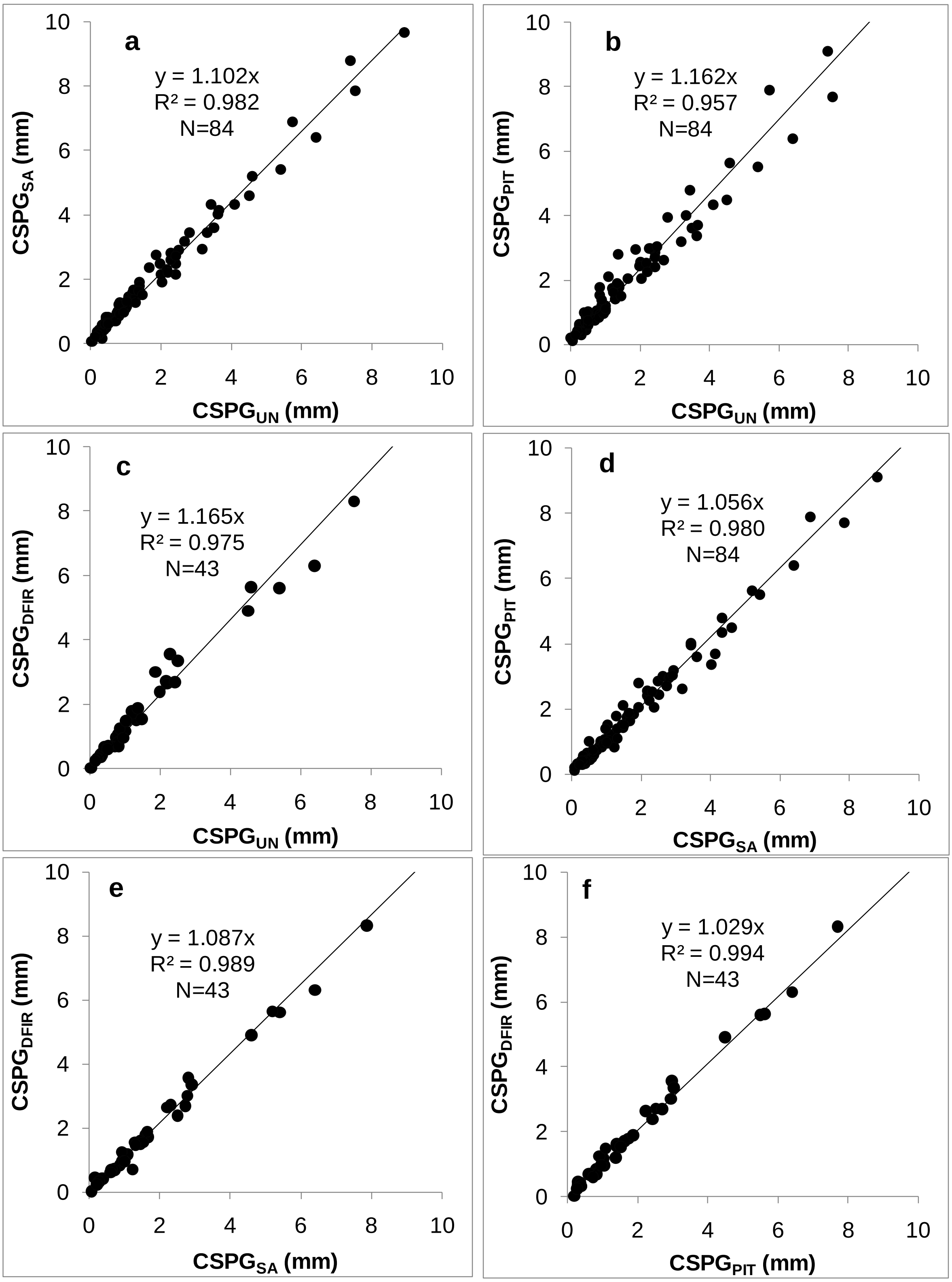

Figure 4. Intercomparison plots among $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ for the snowfall events from September 2010 (**a**, **b** and **d**) or September 2012 (**c**, **e** and **f**) to April 2015**.**

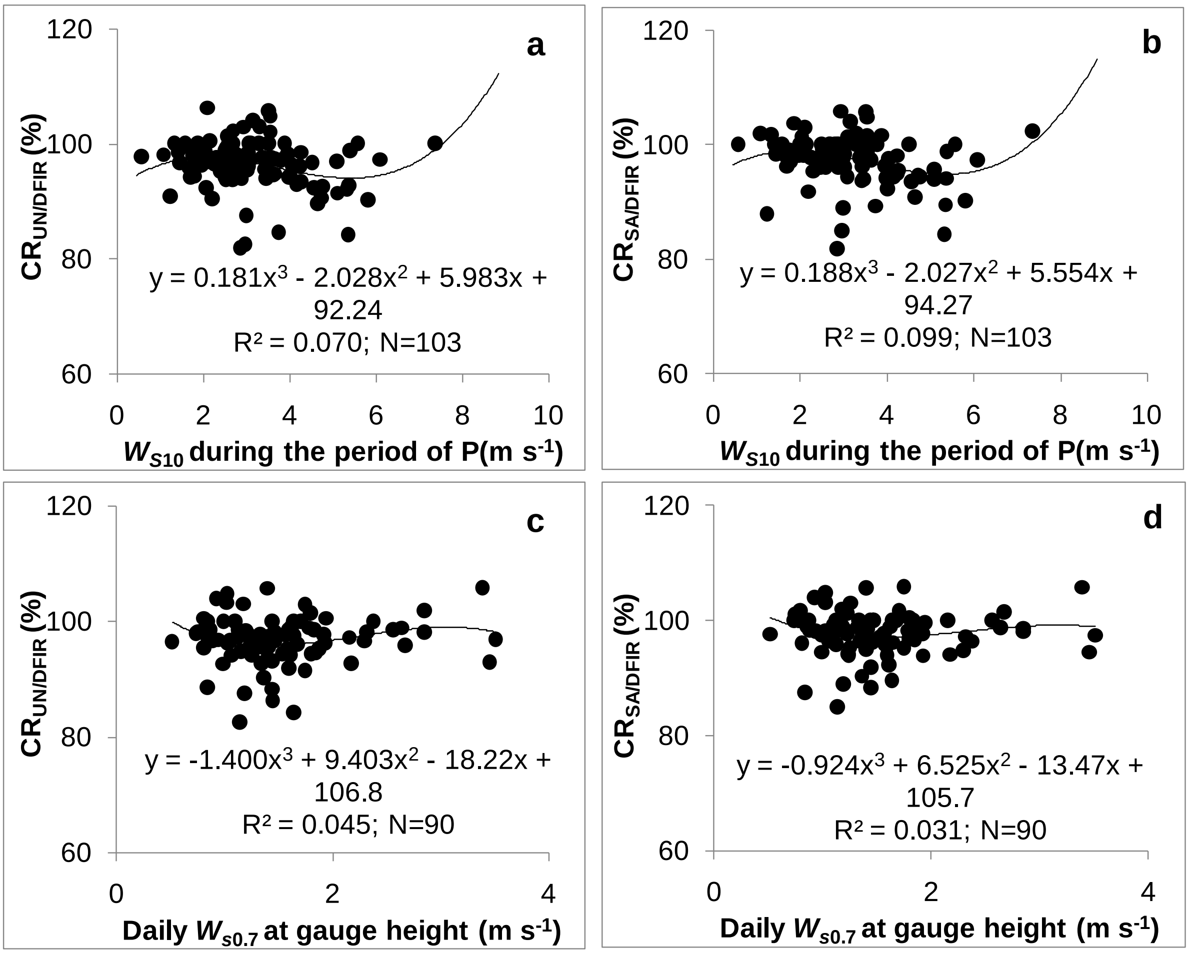

Figure 5. Catch ratios (CRs) vs. wind speed for the rainfall event (**a** and **b**) and the daily rainfall (**c** and **d**) greater than 3.0mm.

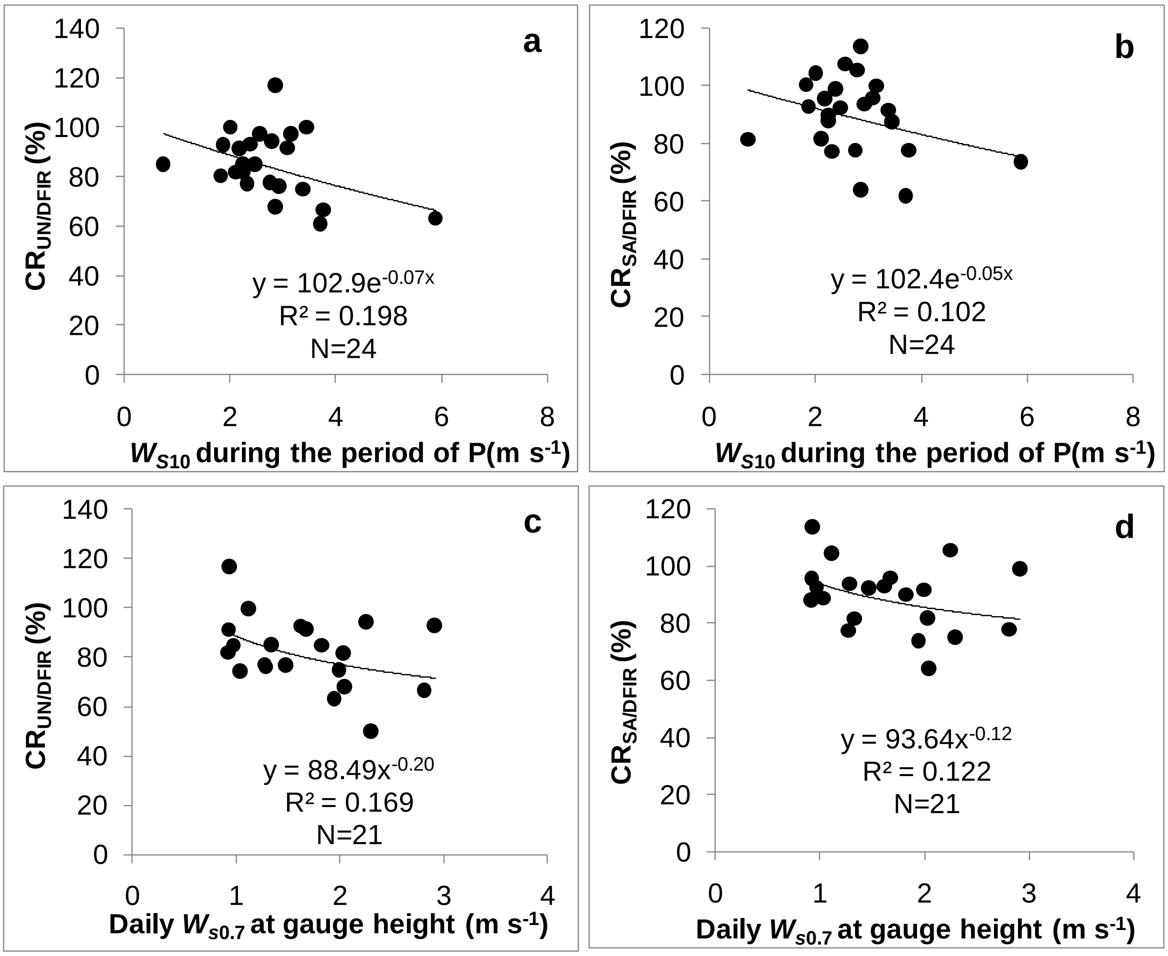

Figure 6. Catch ratios (CRs) vs. wind speed for the mixed precipitation event (**a** and **b**) and the daily mixed precipitation (**c** and **d**) greater than 1.0mm.

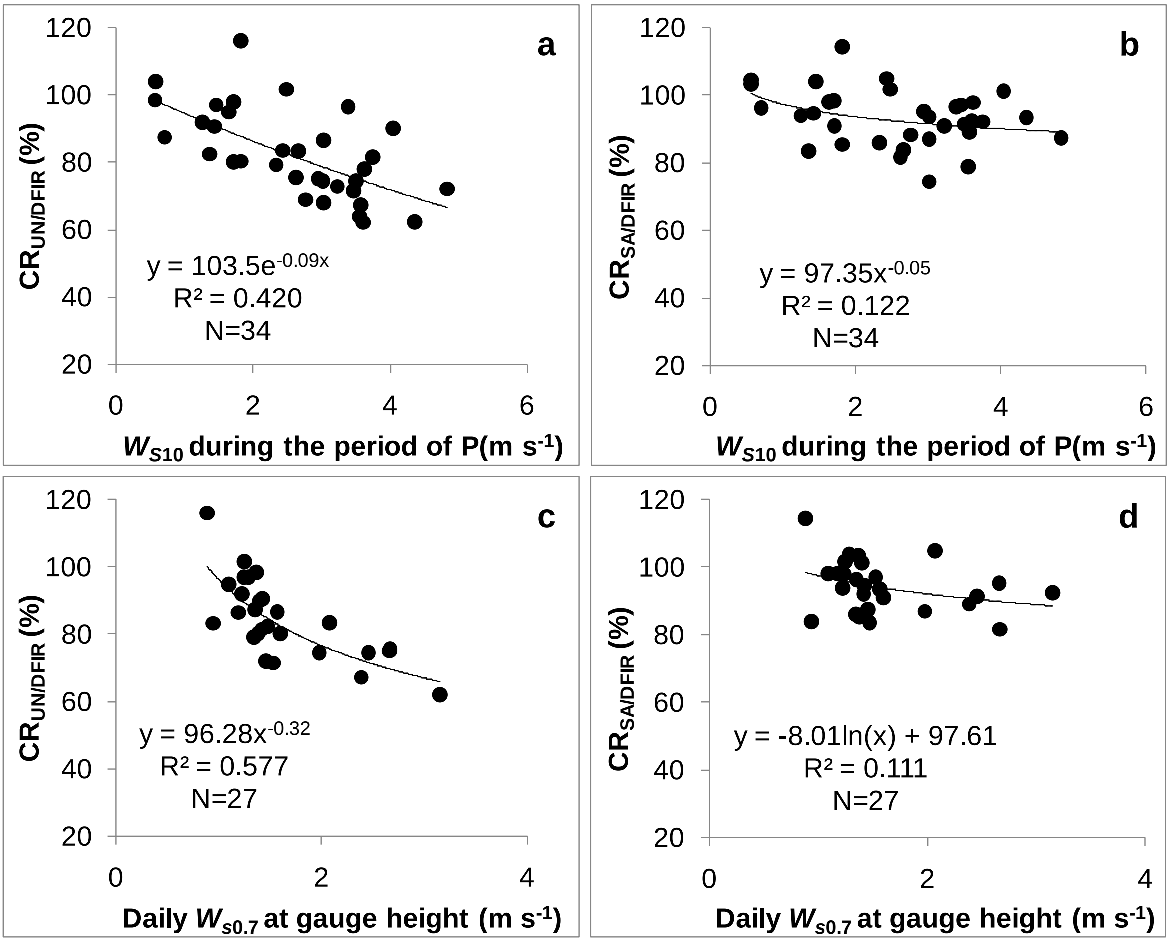

Figure 7. Catch ratios (CRs) vs. wind speed for the snowfall event (**a** and **b**) and the daily (**c** and **d**) snowfall greater than 1.0mm.

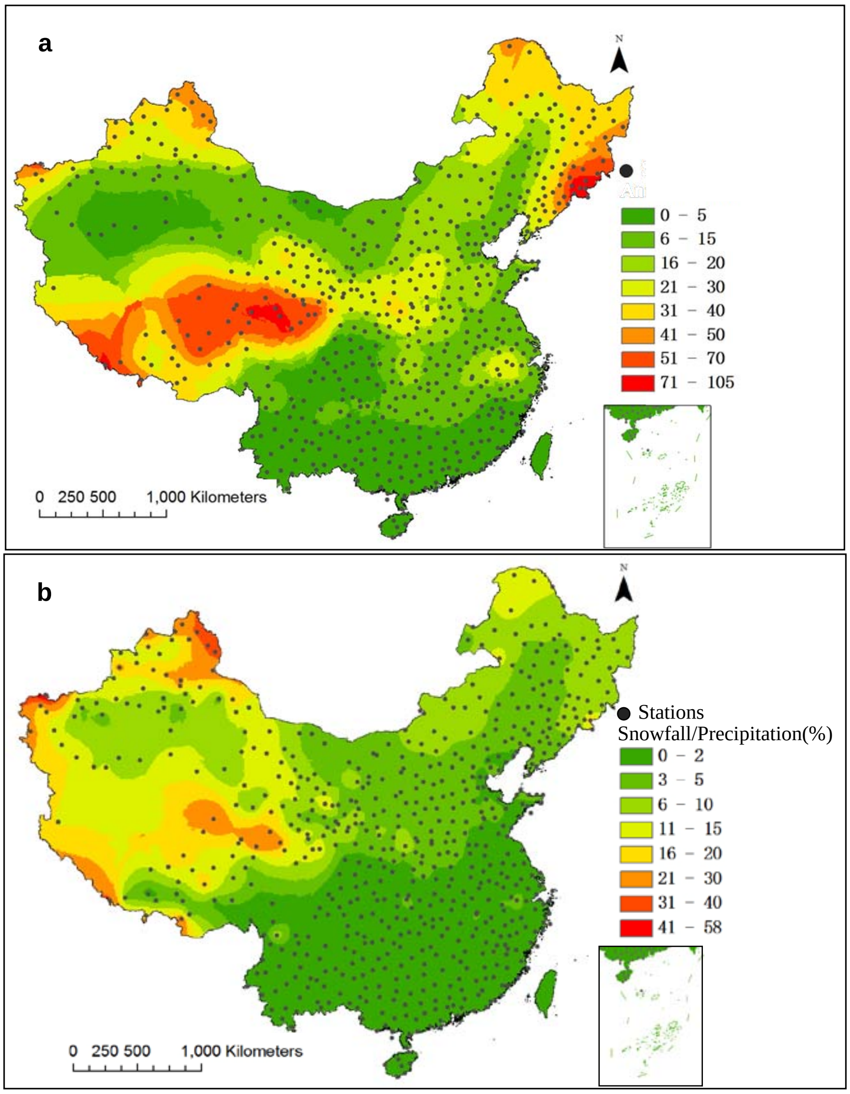

Figure 8. (**a**) Annual snowfall (mm) and (**b**) snowfall proportion (annual snowfall/annual precipitation) in China.

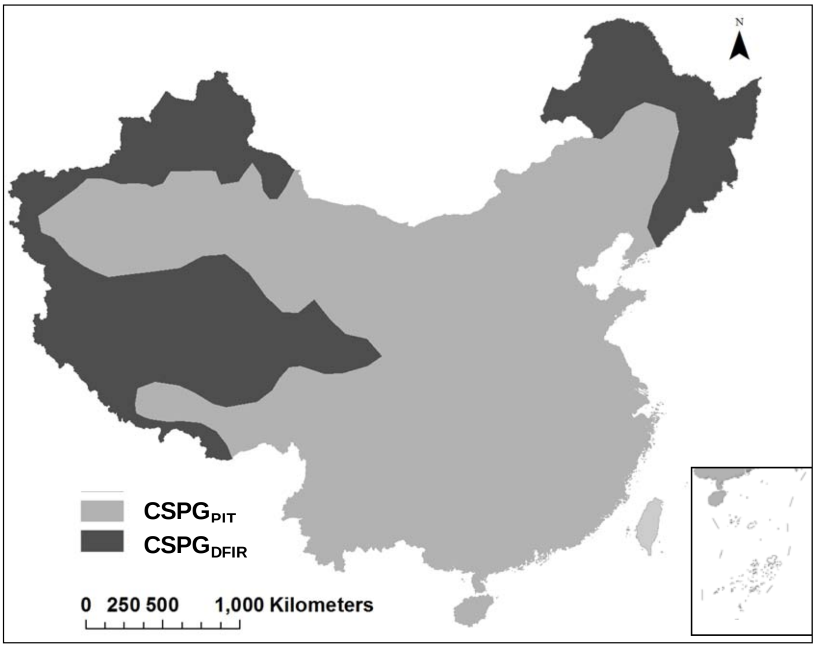

Figure 9. Applicable regions for the $CSPG_{PIT}$ and the $CSPG_{DFIR}$ as reference gauges in China.

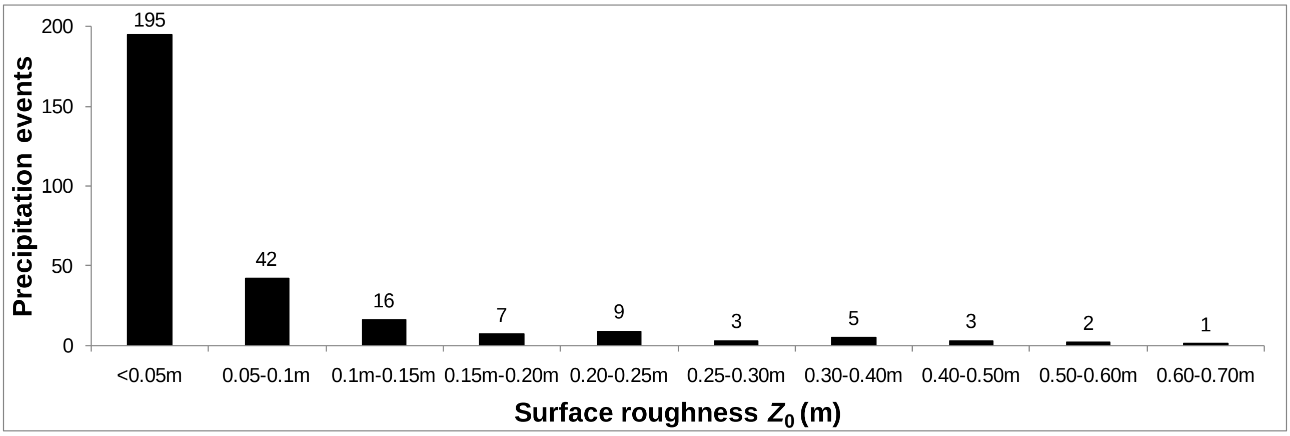

Figure 10. The surface roughness during the precipitation period from September 2012 to April 2015.