

Experimental wind-induced bias in precipitation measurements in a mountain watershed on the north-eastern Tibetan Plateau

R. Chen^{*}, J. Liu, E. Kang, Y. Yang, C. Han, Z. Liu, Y. Song, W. Qing, P. Zhu

Qilian Alpine Ecology and Hydrology Research Station, Key Laboratory of Inland River Ecohydrology, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China

Abstract: An experimental field study of wind-induced bias in precipitation measurements was conducted from September 2010 to April 2015 at a grassland site (99°52.9', 38°16.1', 2980 m) in the Hulu watershed in the Qilian Mountains, on the north-eastern Tibetan Plateau, in China. The experiment included (1) an unshielded Chinese standard precipitation gauge (CSPG_{UN}; orifice diameter=20 cm, height=70 cm), (2) a single Alter shield around a CSPG (CSPG_{SA}), (3) a CSPG in a pit (CSPG_{PIT}) and (4) a Double-Fence International Reference (DFIR) shield with a Tretyakov-shielded CSPG (CSPG_{DFIR}). The catch ratio (CR) used the CSPG_{DFIR} as a reference (CR=CSPG_X/CSPG_{DFIR}, %; X denotes UN, SA or PIT). The results show that the CSPG_{SA}, CSPG_{PIT} and CSPG_{DFIR} 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 (of all types), respectively, than the CSPG_{UN} from September 2012 to April 2015. The CSPG_{PIT} and CSPG_{DFIR} caught 3.6% and 2.5% more 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, respectively, than the CSPG_{SA}. However, 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}. From most to least precipitation measured, the instruments ranked as follows: for rain and mixed precipitation, CSPG_{PIT} > CSPG_{DFIR} > CSPG_{SA} > CSPG_{UN}; for snowfall, CSPG_{DFIR} > CSPG_{PIT} > CSPG_{SA} > CSPG_{UN}. The CR vs. 10 m wind speed for the period of precipitation indicated that with increasing wind speed from 0 to 8.0m/s, the CR_{UN/DFIR} and CR_{SA/DFIR} for rainfall decreased slightly. For mixed precipitation, the wind speed showed no significant effect on CR_{UN/DFIR} and CR_{SA/DFIR} below 3.5m/s. For snowfall, the CR_{UN/DFIR} and CR_{SA/DFIR} vs. wind speed showed that CR decreased with increasing wind speed. The precipitation measured by the shielded gauges increased linearly relative to that of the unshielded gauges independently of the local environmental conditions. However, the increase in the ratio of the linear correlation should depend on specific environmental conditions. A

^{*}Corresponding author. E-mail address:crs2008@lzb.ac.cn (R. Chen)

1 comparison of the wind-induced bias indicates that the $CSPG_{PIT}$ could be used as a reference gauge for rain,
2 mixed and snow precipitation events at the experimental site. As both the PIT and DFIR effectively prevented
3 wind from influencing the catch of the precipitation gauge, the $CR_{PIT/DFIR}$ had no relationship with wind speed.
4 Cubic polynomials and exponential functions were used to simulate the relationship between catch ratio and wind
5 speed. For snow, for both event and daily scales, the $CR_{UN/DFIR}$ and $CR_{SA/DFIR}$ were significantly related to wind
6 speed; while for rain and mixed precipitation, only the event scale showed a significant relationship.

7 **Keywords:** Precipitation, Gauge catch ratio, Wind-induced undercatch, Field observation, Qilian Mountains

8

9 **1 Introduction**

10 In western China, mountainous watersheds are the source areas of runoff generation and water resources, and
11 accurate precipitation measurements are extremely important for calculating the water balance and understanding
12 the water cycle processes in these high mountains. It is widely recognised that precipitation gauge measurements
13 contain systematic errors caused mainly by wetting, evaporation loss and wind-induced undercatch, and that
14 snowfall observation errors are very large under high wind (Sugiura et al., 2003). These errors affect the
15 evaluation of available water in a large number of economic and environmental applications (Tian et al., 2007; Ye
16 et al., 2012).

17 For decades, all knowledge of precipitation measurement errors has relied on field experiments. Back in 1955,
18 the World Meteorological Organization (WMO) conducted the first precipitation measurement intercomparisons
19 (Rodda, 1973). The reference standard was a British Meteorological Office gauge of the Snowdon type (Mk2)
20 elevated 1 m above the ground and equipped with the Alter wind shield, which did not accurately reflect the
21 precipitation level (Struzer, 1971). Rodda (1967) compared the catch of a UK 5" manual gauge, exposed
22 normally at the standard height of 30.5 cm above ground, with a Koschmieder-type gauge exposed in a pit. The
23 gauge in the pit caught 6% more precipitation than the normally exposed gauge. In the second WMO precipitation
24 measurement intercomparison (Rain, 1972–1976), a pit with an anti-splash grid was designated the reference
25 standard shield for rain gauges (Sevruk and Hamon, 1984). In the third WMO precipitation measurement
26 intercomparison (Snow, 1986–1993), the Double Fence International Reference (DFIR) shield with a Tretyakov
27 shield was designated the reference standard snow gauge configuration (Goodison et al., 1998). In the fourth
28 WMO precipitation measurement intercomparison (Rain Intensity, 2004–2008), different principles were tested to
29 measure rainfall intensity and define a standardised adjustment procedure (Lanza et al., 2005). Because

1 automation of precipitation measurements was widespread, the WMO Commission for Instruments and Methods
2 of Observation (CIMO) organised the WMO Solid Precipitation Intercomparison Experiment (WMO-SPICE;
3 Wolff et al., 2014) to define and validate automatic field instruments as references for gauge intercomparison, and
4 to assess the automatic systems and operational networks for precipitation observations. The experiments and
5 investigations are ongoing, and the WMO-SPICE project confirms the DFIR shield to be a part of the reference
6 configurations.

7 The DFIR shield has been operated at 25 stations in 13 countries around the world (Golubev, 1985; Sevruk et
8 al., 2009), but deviations from the DFIR measurements vary by gauge type and precipitation type (Goodison et al.,
9 1998). In China, the Chinese standard precipitation gauge (CSPG) and the Hellmann gauge were first compared
10 using the DFIR shield as a reference configuration at the Tianshan site (43°7' N, 86°49' E, 3720 m), during the
11 third WMO precipitation measurement intercomparison experiment from 1985 to 1987 (Yang, 1988; Yang et al.,
12 1991). The wetting loss, evaporation loss, wind-induced undercatch and trace precipitation of the CSPGs were
13 well quantified based on the huge volume of observation data at the Tianshan site (Yang et al., 1991). For
14 wind-induced undercatch, the derived CSPG catch ratio equations were based on the 10 m height wind speed at
15 the Daxigou Meteorological Station (43.06°, 86.5°E, 3540 m) and at several other standard meteorological
16 stations near the measurement site (Yang, 1988; Yang et al., 1991). This intensive experimental field study created
17 a basis for later work on the correction of systematic bias in precipitation measurements in China. From 1992 to
18 1998, Ren and Li (2007) conducted an intercomparison experiment at 30 sites (the altitude ranged from about 4.8
19 to 3837 m) using the pit as a reference across China, and a total of 29, 276 precipitation events were observed.
20 Yang et al. (1999) emphasised that among all known systematic errors in precipitation observation, wind-induced
21 gauge undercatch was the greatest source of bias, particularly in cold regions, and recommended testing for the
22 application of adjustment techniques in regional observation networks. In the mountainous watersheds of western
23 China, the complex high mountain topography and underlying surfaces with inhomogeneous glaciers, permafrost
24 and alpine vegetation make the wind vector field in the lower boundary layer extremely complex, causing equally
25 complex wind field deformations over the gauge orifice. At present, our investigation of wind-induced error in
26 precipitation measurements is based on the horizontal time-averaged wind speed. Thus it is reasonable to
27 investigate the regional average characteristics of wind fields and the interaction between wind fields and the
28 precipitation gauges at our present research level. In addition to Yang's experimental field work on systematic
29 error adjustments for precipitation measurements in eastern Tianshan from 1985 to 1987 (Yang, 1988), it is very
30 necessary to carry out field experiments on precipitation measurement in the other mountainous regions of

1 western China.

2 Adjustment procedures and reference measurements were developed during several WMO international
3 precipitation measurement intercomparisons (Goodison et al., 1998; Sevruk et al., 2009; Yang, 2014). The
4 application of all of these adjustment procedures and methods depends on both environmental factors and
5 precipitation features, and among the factors considered, wind speed and temperature have been found to have the
6 most important effect on gauge catch (Yang et al., 1999). Ye et al. (2004, 2007) developed a bias-error adjustment
7 method for CSPGs based on observation data from 1985 to 1997 at the Tianshan site (Yang et al., 1991), and
8 found a new precipitation trend in the adjusted precipitation data for the past 50 years in China (Ding et al., 2007).
9 The new precipitation adjustment has improved the precipitation estimation in water balance computation for
10 many basins in China (Ye et al., 2004; Tian et al., 2007; Ye et al., 2012). Ma et al. (2014) used the adjusted
11 equations from neighbouring countries in addition to the experimental results from eastern Tianshan in China
12 (Yang et al., 1991) to correct for wind-induced errors on the Tibetan Plateau. However, the precipitation gauges
13 used in the neighbouring countries were the Tretyakov, MK2, Nepal203, Indian standard and US 8". As the
14 world's third polar region, the Tibetan Plateau and its surrounding mountain ranges are ecologically fragile and
15 the source of several large rivers in China and neighbouring countries, and accurate precipitation data are urgently
16 needed for water resource exploitation and environmental protection. The problem is how to apply and test the
17 already established principal adjustment procedures and methods to correct for precipitation measurement errors
18 in the vast plateau and high mountains of western China, where climatic and environmental conditions are highly
19 complex and variable, both spatially and temporally. To quantify and understand the specific influences of
20 climatic and environmental factors on wind-induced bias in precipitation measurements in a mountain watershed,
21 and then test and parameterise the adjustment equations, an intercomparison experiment was carried out for nearly
22 five years on both unshielded and shielded CSPGs in a watershed in the Qilian Mountains on the north-eastern
23 Tibetan Plateau in China.

24 The CSPG is the standard manual precipitation gauge that has been used by the China Meteorological
25 Administration (CMA) in more than 700 stations since the 1950s. The present experiment is to investigate the
26 wind-induced bias of the CSPG in the high mountain environment. Therefore, a single Alter shield (SA) (Struzer,
27 1971), a Double-Fence International Reference shield with a Tretyakov-shielded (DFIR) and a pit were selected to
28 shield the CSPGs, which were distributed by an unshielded CSPG. The SA shield is used by the CMA to enhance
29 the catch ratios of automatic gauges (Yang, 2014), and the DFIR was used to provide true snowfall values for the
30 WMO intercomparison project (Yang et al., 1999). This paper presents the intercomparison experiments and their

1 relevant data, introduces the adjustment methods, discusses wind-induced bias in precipitation measurements by
2 CSPGs for different precipitation phases, analyses the correlations between shielded and unshielded CSPGs and
3 specifies the relationships between catch ratio and wind speed. The results of the present study are also compared
4 with other studies. In addition, the pit shield is evaluated for solid precipitation under these climatic conditions.
5 The limitations of the present study are then discussed.

6 **2 Experiments and methods**

7 **2.1 Intercomparisons and data**

8 Precipitation intercomparison experiments (Fig.1, Table 1) were conducted at a grassland site (99°52.9',
9 38°16.1', 2980 m) in the Hulu watershed in the Qilian Mountains, on the north-eastern edge of the Tibetan Plateau,
10 in China. A meteorological cryosphere-hydrology observation system (Chen et al., 2014) was established in 2008
11 in the Hulu watershed. The mean annual precipitation was 447.2 mm during 2010-2012 and was concentrated
12 during the warm season from May to September. The annual mean temperature was 1.1 °C, with a July mean
13 (T_{mean}) of 12.5 °C and a January mean of -12.4°C over the years (Table 1). The annual potential evaporation (E_0)
14 was 1102 mm (Table 1).

15 The intercomparative experiments included (1) an unshielded CSPG (CSPG_{UN}; orifice diameter=20 cm,
16 height=70 cm), (2) a single Alter shield around a CSPG (CSPG_{SA}), (3) a CSPG in a pit (CSPG_{PIT}), and (4) a DFIR
17 shield with a Tretyakov-shielded CSPG (CSPG_{DFIR}) (Fig.1, Table 2). The CSPG_{UN}, CSPG_{SA} and CSPG_{PIT} were
18 installed before September 2010, whereas the CSPG_{DFIR} was installed in September 2012 (Table 2). In the cold
19 season (October to April), snowfalls dominated the precipitation events, and in the warm season (May to
20 September), rainfall was dominant. The precipitation was measured manually twice a day at 08:00 and 20:00 local
21 time (Beijing time) according to the CMA's criteria (CMA, 2007a). In the warm season, precipitation was
22 measured by volume. Whereas in the cold season, the funnel and glass bottle were removed from the CSPG and
23 precipitation was weighed under a windproof box. Any frost on the outside surface of the collector was wiped off
24 using a dry hand towel. In rare cases where snow had accumulated on the rim of the collector, this was removed
25 before weighing.

26 The precipitation phases (snow, rain and mixed) were distinguished using the CMA's criteria (CMA, 2007b).
27 Meteorological elements, including maximum air temperature T_{max} and minimum T_{min} , have been measured in
28 conformation with the meteorological observation manual at the site since June, 2009. A meteorological tower
29 was used to measure wind speed (Lisa/Rita, SG GmbH; W_s), air temperature (HMP45D, Vaisala) and relative

1 humidity (HMP45D, Vaisala) at 1.5m and 2.5m heights in association with precipitation measurements (Chen et
2 al., 2014). The time step of the observations of the tower was 30 seconds and half-hourly values were obtained.
3 The specific meteorological conditions at the site are summarised in Table 1.

4
5 **Fig.1 about here**

6 **Table 1 and Table 2 about here**

7 **2.2 Adjustment methods**

8 This field experiment focused on two key aspects. One was a comparison of the CSPG_{UN}, CSPG_{SA}, CSPG_{PIT}
9 and CSPG_{DFIR} gauges. The other was the establishment of adjustment equations for the CSPG_{UN} and CSPG_{SA}
10 using the CSPG_{DFIR} as a reference. To adjust gauge-measured precipitation, Sevruk and Hamon (1984) provided
11 the general formula as:

$$12 \quad P_c = KP_g + \Delta P_w + \Delta P_e + \Delta P_t = P_{DFIR} + \Delta P_w + \Delta P_e + \Delta P_t \quad (1)$$

13 where P_c is the adjusted precipitation, K is the wind-induced coefficient, P_g is the gauge-measured precipitation.
14 P_w is the wetting loss, P_e is the evaporation loss, P_t is trace precipitation and P_{DFIR} is the DFIR-shielded
15 precipitation. For loss by the CSPG per observation, P_w is 0.23 mm for rainfall measurements, 0.30 mm for snow
16 and 0.29 mm for mixed precipitation (snow with rain, rain with snow), based on the measurements at the Tianshan
17 site (Yang, 1988; Yang et al., 1991). Ren and Li (2007) reported a mean P_w of about 0.19 mm for the total
18 precipitation over eastern China. The CSPG design reduces P_e to a near-zero value smaller than other losses in the
19 warm, rainy season (Ye et al., 2004; Ren and Li, 2007). In winter, P_e is already small (0.10–0.20 mm/day)
20 according to the results from Finland (Aaltonen et al., 1993) and Mongolia (Zhang et al., 2004). To prevent
21 evaporation loss in Chinese operational observations on particular days, e.g., hot, dry days or days of snow,
22 precipitation is measured as soon as the precipitation event stops (CMA, 2007a; Ren and Li, 2007). A
23 precipitation event of less than 0.10 mm is beyond the resolution of the CSPG and is recorded as trace
24 precipitation (P_t). Ye et al. (2004) recommended assigning a value of 0.1 mm, regardless of the number of trace
25 observations per day. The present study focused on wind-induced bias in precipitation measurement by CSPGs,
26 specifically in high mountain environments, therefore the above mentioned P_w , P_e and P_t values were assumed to
27 be constant in the computation equations.

28 The WMO proposed Eqs.(2)–(4) to compute the catch ratio of unshielded over shielded Tretyakov gauges on a
29 daily time step for three precipitation types, and the independent variables were wind speed (W_s , ms^{-1}) at the
30 gauge height and the daily maximum and minimum temperatures (T_{max} , T_{min} , °C) (Yang et al., 1995; Goodison et

1 al., 1998). These equations are used over a great range of environmental conditions (Goodison et al., 1998).

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

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

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

5

6 where CR_{snow} (%), CR_{mix} (%) and CR_{rain} (%) are the catch ratios for snow, mixed precipitation and rain,
7 respectively.

8 As the CMA stations usually observe wind speed at a height of 10m, Eqs.(5)–(7) were used for the CSPG catch
9 ratio versus the daily mean wind speed W_s (ms^{-1}) at 10m (Yang et al., 1991). These equations are based on the
10 huge volume of experimental precipitation gauge intercomparison data at the Tianshan site and the wind speed
11 data at the Daxigou station:

$$12 \quad CR_{snow} = 100 \exp(-0.056W_{s10}) \quad (0 < W_s < 6.2) \quad (5)$$

$$13 \quad CR_{rain} = 100 \exp(-0.04W_{s10}) \quad (0 < W_s < 7.3) \quad (6)$$

$$14 \quad CR_{mix} = CR_{snow} - (CR_{snow} - CR_{rain})(T_{mean} + 2) / 4 \quad (7)$$

15 where T_{mean} is the daily mean air temperature ($^{\circ}C$).

16 Referring to Eqs.(2)–(7), two types of equation were used. One is for easy application using the 10m height
17 wind speed during the period of precipitation in China. These are similar to a revised version of Eqs.(5)–(7). The
18 other type is similar to Eqs.(2)–(4), which use the daily mean wind speed at gauge height. For the CSPGs, the
19 gauge height was 70cm (Table 2). The catch ratio uses $CSPG_{DFIR}$ as the reference ($CR=CSPG_X/CSPG_{DFIR}$, %; X
20 denotes UN, SA or PIT). The equations were fitted using SPSS software version 19.0 (IBM, 2010) and Microsoft
21 Excel 2007 based on the mathematical least squares method (Charnes et al., 1976). The significance of the
22 equations was evaluated using the F-test method (Snedecor and Cochran, 1989). If the significance level (α) of the
23 F-test is below 0.05, the fitted equation is significant. The lower the α value, the greater the significance.

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

$$26 \quad W_{sZ} = \frac{\ln Z - \ln Z_0}{\ln 1.5 - \ln Z_0} W_{s1.5} \quad (8)$$

$$27 \quad \ln Z_0 = \frac{W_{s2.5} \ln 1.5 - W_{s1.5} \ln 2.5}{W_{s2.5} - W_{s1.5}} \quad (9)$$

28 where Z denotes the height referred to.

1 **3 Results**

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

7

8

Table 3 about here

9

10 **3.1 Linear correlation of gauge precipitation**

11 At the 14 WMO intercomparison sites, a strong linear relationship was found between Alter-shielded and
12 unshielded Belfort gauges, Alter-shielded and unshielded NWS 8-inch gauges, and shielded and unshielded
13 Tretyakov gauges for all types of precipitation, with a higher correlation for rain than for snow (Yang et al., 1999).
14 In the present study in the Qilian Mountains, which experiences different environmental conditions compared to
15 the other 14 sites, the same strong linear correlation was found among the four CSPG instalments for rainfall,
16 mixed precipitation and snowfall, with a higher correlation for rain than for mixed precipitation, successively
17 more than for snow (Figures 2–4). It is therefore considered that in general the precipitation measured by shielded
18 gauges increases linearly with that of unshielded gauges, independently of local environmental conditions.
19 However, the relative increase in linear correlation should depend on the specific environmental conditions. For
20 solid precipitation, some non-linear factors interfered with the linear relationship to reduce the correlation
21 coefficient.

22

23

Fig.2 about here

24

Fig.3 about here

25

Fig.4 about here

26

27 **3.2 Comparisons of wind-induced bias**

28 **3.2.1 Rainfall**

29 From September 2010 to April 2015, the CSPG_{PIT} caught 4.7% and 3.4% more rainfall than the CSPG_{UN} and

1 the CSPG_{SA} respectively $((\text{CSPG}_{\text{PIT}} - \text{CSPG}_{\text{UN}}) / \text{CSPG}_{\text{UN}} * 100$; similarly hereinafter). The CSPG_{SA} caught 1.3%
2 more rainfall than the CSPG_{UN} (Table 3).

3 During the period from September 2012 to April 2015, the CSPG_{SA}, CSPG_{PIT} and CSPG_{DIFR} caught 0.9%, 4.5%
4 and 3.4% more rainfall, respectively, than the CSPG_{UN}, and the CSPG_{PIT} and CSPG_{DIFR} caught 3.6% and 2.5%
5 more rainfall, respectively, than the CSPG_{SA}. However, the CSPG_{DIFR} caught 1.0% less rainfall than the CSPG_{PIT}
6 (Table 3, Fig.2). These comparative results indicate that the CSPG_{PIT} caught more rainfall and total precipitation
7 compared to the CSPG_{DIFR} and other gauges at the experimental site (Table 3, Fig.2).

8 **3.2.2 Mixed precipitation**

9 From September 2012 to April 2015, a total of 29 mixed precipitation events were observed. As shown in Table
10 3, the CSPG_{PIT} caught the most mixed precipitation among the gauges, capturing 82.2 mm of mixed precipitation
11 in 29 events, but only 1.1 mm more than the CSPG_{DIFR}. The linear relationship between the CSPG_{PIT} and
12 CSPG_{DIFR} is statistically significant with an R^2 value of about 0.98 (Fig.3f). Thus for mixed precipitation, in
13 addition to the CSPG_{DIFR}, the CSPG_{PIT} could also be selected as a reference gauge for the CSPG_{UN} and CSPG_{SA} at
14 the experimental site.

15 **3.2.3 Snowfall**

16 From September 2012 to April 2015, the CSPG_{SA}, CSPG_{PIT} and CSPG_{DIFR} caught 11.1%, 16.0% and 20.6%
17 more snowfall, respectively, than the CSPG_{UN}, and the CSPG_{PIT} and CSPG_{DIFR} caught 4.4% and 8.5% more
18 snowfall, respectively, than the CSPG_{SA} (Table 3).

19 Although the CSPG_{DIFR} caught 3.9% more snowfall compared to the CSPG_{PIT} (Table 3), the difference in total
20 snowfall (43 events) between the CSPG_{DIFR} and CSPG_{PIT} was only about 3.4 mm (Table 3). Their linear
21 correlation was highly significant with an R^2 value of 0.994 (Fig.4f). Blowing snow and thick snow cover have
22 traditionally limited the pit's use as a reference shield for snowfall and mixed precipitation. At the experimental
23 site, blowing snow was rarely observed and the snow cover was usually shallow. This suggests that the CSPG_{PIT}
24 could be used as a reference gauge for snow precipitation events at the experimental site.

25 To sum up the comparisons of wind-induced bias, from most to least rainfall and mixed precipitation measured,
26 the instruments ranked as follows: CSPG_{PIT} > CSPG_{DIFR} > CSPG_{SA} > CSPG_{UN}, while for snowfall their ranking was
27 CSPG_{DIFR} > CSPG_{PIT} > CSPG_{SA} > CSPG_{UN}.

28 **3.3 Catch ratio vs. wind speed**

29 Previous studies have shown that wind speed during the precipitation period is the most significant variable

1 affecting gauge catch efficiency (Metcalf and Goodison, 1993; Yang et al., 1995; Goodison et al., 1998). Because
 2 the CMA stations observe wind speeds at the 10m height, the $CSPG_{UN}$ and $CSPG_{SA}$ adjustment equations for a
 3 single precipitation event were obtained for 10m height wind speeds. On the daily scale, adjustment equations
 4 similar to Eqs.(2)–(4) were also obtained, based on the daily mean wind speed converted to gauge height (0.7m
 5 for the CSPGs) and air temperature.

6 To minimise ratio scatter for the different gauges, precipitation events greater than 3.0 mm are normally
 7 selected for the CR vs. wind analysis (Yang et al. 1995; Yang et al., 2014). However, in the Hulu watershed, most
 8 snowfall and mixed precipitation events were less than 3.0 mm, thus the limit was reduced and single or daily
 9 snowfall and mixed precipitation events greater than 1.0 mm were selected, while rainfall events greater than 3.0
 10 mm were selected. The numbers of selected precipitation events are shown in Table 4. The CR vs. wind speed
 11 relationships for different precipitation types were simulated using cubic polynomials and exponential functions
 12 and were summarised in Table 4. The $CR_{UN/DFIR}$ and $CR_{SA/DFIR}$ vs. wind speed relationships are statistically
 13 significant, but the $CR_{PIT/DFIR}$ vs. $W_{s0.7}$ or W_{s10} relationships do not pass the F-test with $\alpha=0.10$. This phenomenon
 14 indicates that both PIT and DFIR are effective in preventing wind from influencing the gauge catch of
 15 precipitation, therefore the $CR_{PIT/DFIR}$ is not related to wind speed.

16
 17 **Table 4 about here**
 18

19 Fig.5 presents scatter plots for the $CR_{UN/DFIR}$ and $CR_{SA/DFIR}$ vs. wind speed for rainfall. The CRs vary from 80%
 20 to 110%. With increasing wind speed, the CRs decrease slightly. Only Eq. (10) shown in Fig.5 and Table 4 could
 21 be used to adjust the rainfall event data from the $CSPG_{SA}$. It is significant at 0.03 level (Table 4). As described in
 22 section 2.2, Eq.(10) was fitted using the NONLINEAR function in SPSS software
 23 (Analyze\Regression\Nonlinear). The F-value was then calculated using regression and the residual sum of
 24 squares from SPSS (Snedecor and Cochran, 1989). Based on the F-value and the degrees of freedom (Df), the
 25 significance level (α) was obtained using the FDIST function in Microsoft Excel. Other forms such as the
 26 exponential expression were treated in a similar way.

$$27 \quad CR_{SA/DFIR,Rain} = 0.188W_{s10}^3 - 0.719W_{s10}^2 + 0.551W_{s10} + 100 \quad 0 < W_{s10} < 7.4 \quad (10)$$

28 where $CR_{SA/DFIR,Rain}$ is the rainfall catch ratio (%) per observation of the $CSPG_{SA}$ and W_{s10} is the wind speed at
 29 10m during the rainfall period ($m s^{-1}$).

1 **Fig.5 about here**

2
3 On the daily scale, the relationships between rainfall CR and wind speed at gauge height ($W_{s0.7}$) are also cubic
4 functions, but they do not pass the F-test with $\alpha=0.25$ (Table 4).

5 For the mixed precipitation events, the CR vs. W_{s10} relationships are exponential (Table 4, Fig.6). The CRs vary
6 greatly from about 60% to 120%. For the CSPG_{UN}, the exponential relationship Eq. (11) passes the F-test with
7 $\alpha=0.07$, whereas for the CSPG_{SA}, the Eq.(12) α value is about 0.16 (Table 4).

8
9 **Fig.6 about here**

10
11
$$CR_{UN/DFIR,Mixed} = 100e^{-0.06W_{s10}} \quad 0 < W_{s10} < 5.9 \quad (11)$$

12
$$CR_{SA/DFIR,Mixed} = 100e^{-0.04W_{s10}} \quad 0 < W_{s10} < 5.9 \quad (12)$$

13 On the daily scale, the relationships between mixed precipitation CR and wind speed at gauge height ($W_{s0.7}$) are
14 also exponential expressions (Table 4, Fig.6). Similarly, for the CSPG_{UN}, Eq. (13) passes the F-test with $\alpha < 0.10$,
15 whereas Eq.(14) with an α value of about 0.18 doesn't (Table 4).

16
$$CR_{UN/DFIR,Mixed} = 100e^{-0.12W_{s0.7}} \quad 0 < W_{s0.7} < 2.9 \quad (13)$$

17
$$CR_{SA/DFIR,Mixed} = 100e^{-0.07W_{s0.7}} \quad 0 < W_{s0.7} < 2.9 \quad (14)$$

18 From Eq. (3), air temperature may also affect the mixed precipitation CRs on the daily scale. Eqs. (15)–(16) are
19 obtained as follows. However, these two new equations do not pass the F-test with $\alpha < 0.20$.

20
$$CR_{UN/DFIR,Mixed} = 13.83W_{s0.7}^{-4.91} + 1.25T_{\max} - 0.88T_{\min} + 62.21 \quad \alpha=0.20 \quad (15)$$

21
$$CR_{SA/DFIR,Mixed} = 10.74W_{s0.7}^{-4.74} + 0.85T_{\max} - 0.18T_{\min} + 76.20 \quad \alpha=0.29 \quad (16)$$

22 where T_{\max} and T_{\min} are the daily maximum and minimum air temperature ($^{\circ}\text{C}$), respectively.

23 For the snowfall events, the $CR_{UN/DFIR,Snow}$ and $CR_{SA/DFIR,Snow}$ vs. W_{s10} relationships are significant (Table 4,
24 Fig.7). For the CSPG_{UN}, the exponential relationship Eq.(17) passes the F-test with $\alpha < 0.001$. Eq.(17) is similar to
25 Eq.(5) suggested by Yang et al. (1991). For the CSPG_{SA}, its exponential expression in Eq.(18) passes the F-test at
26 $\alpha=0.07$ (Table 4).

27
28 **Fig.7 about here**

1

$$2 \quad CR_{UN/DFIR,Snow} = 100e^{-0.08W_{s10}} \quad 0 < W_{s10} < 4.8 \quad (17)$$

$$3 \quad CR_{SA/DFIR,Snow} = 100e^{-0.02W_{s10}} \quad 0 < W_{s10} < 4.8 \quad (18)$$

4 On the daily scale, the relationships between snowfall CRs and wind speed at gauge height ($W_{s0.7}$) are also
 5 exponential expressions (Table 4, Fig.7). For the $CSPG_{UN}$ and $CSPG_{SA}$, the Eqs.(19)–(20) pass the F-test with
 6 $\alpha < 0.001$ and $\alpha = 0.14$, respectively (Table 4). Eqs. (17)–(19) could therefore be directly used to calibrate the
 7 wind-induced snowfall measurement errors for the $CSPG_{UN}$ and $CSPG_{SA}$.

$$8 \quad CR_{UN/DFIR,Snow} = 100e^{-0.11W_{s0.7}} \quad 0 < W_{s0.7} < 3.1 \quad (19)$$

$$9 \quad CR_{SA/DFIR,Snow} = 100e^{-0.03W_{s0.7}} \quad 0 < W_{s0.7} < 3.1 \quad (20)$$

10 Air temperature may also affect the snowfall CR on the daily scale as shown in Eq.(2). Eqs. (21)–(22) are the
 11 new equations associated with daily maximum air temperature. However, these two new equations are no better
 12 than Eqs. (19)–(20) according to their F-test α values.

$$13 \quad CR_{UN/DFIR,Snow} = 42.29W_{s0.7}^{-1.06} - 1.06T_{max} + 55.91 \quad \alpha = 4.2E-5 \quad (21)$$

$$14 \quad CR_{SA/DFIR,Snow} = -9.46\ln(W_{s0.7}) - 0.31T_{max} + 98.76 \quad \alpha = 0.17 \quad (22)$$

15 From the above mentioned relationships of $CR_{UN/DFIR}$ and $CR_{SA/DFIR}$ vs. wind speed, the following points can be
 16 drawn for our understanding. For daily rain and mixed precipitation, the relationships are not statistically
 17 significant. Daily maximum and minimum temperatures should reflect the atmospheric conditions of radiation and
 18 convection to some degree, and their function in the CR vs. wind speed relationship needs further investigation in
 19 a mountain environment.

20 **4 Discussion**

21 **4.1 Comparison with other studies**

22 Yang et al. (1991) carried out a precipitation intercomparison experiment from 1985 to 1987 at the Tianshan
 23 site. Their results indicated that the $CSPG_{DFIR}/CSPG_{UN}$ ratios for snowfall and mixed precipitation were 1.222 and
 24 1.160, respectively. In the Hulu watershed, these ratios were 1.165 (Fig.4c) and 1.072 (Fig.3c), while those for
 25 $CSPG_{PTT}/CSPG_{UN}$ were 1.162 (Fig.4b) and 1.082 (Fig.3b), respectively. Similar topographic features and shading
 26 induced similar lower wind speeds and led to similar catch ratios at both sites. For the Tianshan reference site,
 27 wind speed (W_{s10}) on rainfall or snowfall days never exceeded 6 m s^{-1} , and 88% of the total annual precipitation
 28 took place with wind speeds below 3 m s^{-1} . At the Hulu watershed site, daily mean wind speeds (W_{s10}) on
 29 precipitation days never exceeded 6.4 m s^{-1} , and over 55.2% of the precipitation events occurred with daily mean

1 wind speeds below 3 m s^{-1} . During the periods of precipitation, the largest wind speed at the 10m height was about
2 8.8 m s^{-1} , and over 54.2% of the precipitation events occurred with wind speeds below 3 m s^{-1} .

3 As Ren et al. (2003) reported, across 30 comparison stations in China, the CSPG_{PIT} caught 3.2% (1.1~7.9%)
4 more rainfall and 11.0% (2.2~24.8%) more snowfall compared to the CSPG_{UN} . Large wind-induced differences
5 were often observed at the mountainous western stations and in north-eastern China. At the Gangcha station
6 ($100^{\circ}08'$, $37^{\circ}20'$, 3015 m), which also lies in the Qilian Mountains at a similar elevation about 200 km from the
7 Hulu watershed site, the CSPG_{PIT} caught 7.9% more rainfall and 16.8% more snowfall than the CSPG_{UN} from
8 1992 to 1998. In our study, the CSPG_{PIT} captured 4.7% more rainfall, 21.0% more snowfall and 12.1% more
9 mixed precipitation than the CSPG_{UN} from September 2010 to April 2015 (Table 3). The outcome presented in
10 this study is somewhat different from that reported by Ren et al. (2003) due to differences in the wind regime. At
11 the Gangcha station, daily mean wind speeds (W_{s10}) on precipitation days during the experimental period from
12 1992 to 1998 never exceeded 8.5 m s^{-1} , and over 35.1% of the precipitation events occurred with daily mean wind
13 speeds below 3 m s^{-1} . The average daily mean W_{s10} was about 3.4 m s^{-1} on precipitation days from 1992 to 1998 at
14 the Gangcha station, whereas at the Hulu watershed site from 2010 to 2015, the average value was about 2.9 m s^{-1}
15 on precipitation days.

16 It is recognised that in western China, climatic and environmental conditions in the mountains vary both
17 spatially and temporally. To understand the similarities and differences in wind-induced bias in precipitation
18 measurements for different mountain watersheds, field experiments need to be carried out continuously.

19 **4.2 CSPG_{PIT} as a reference for solid precipitation**

20 The pit is the WMO reference configuration for liquid precipitation measurements and the DFIR is the
21 reference configuration for solid precipitation measurements (Sevruk et al., 2009). In this study, the CSPG_{PIT}
22 measured more rainfall and mixed precipitation than the $\text{CSPG}_{\text{DFIR}}$. For snowfall, the catch ratio for CSPG_{PIT} was
23 0.96, close to that of the $\text{CSPG}_{\text{DFIR}}$ measurement. The difference in total snowfall (43 events) between the
24 CSPG_{PIT} and $\text{CSPG}_{\text{DFIR}}$ was only about 3.4 mm from September 2012 to April 2015 at the Hulu watershed site.
25 The snowfall for autumn and spring was greater than for winter during the observation period at the
26 intercomparison site (Fig.8). The snowfall is wetter in autumn and spring than in winter, and wetter snowfall
27 means less blowing or drifting snow. Thus the CSPG_{PIT} could serve as a reference for liquid and solid
28 precipitation in environments similar to that of the Hulu watershed site. Precipitation collected by the CSPG_{PIT}
29 would be most affected by blowing or drifting snow, inducing a faulty precipitation value (Goodison et al., 1998;

1 Ren and Li, 2007). Previous studies have indicated, however, that for most of China the maximum snow depth in
2 the past 30 years has been less than 20 cm (Li, 1999), with average snow depths below 3 cm (Li et al., 2008; Che
3 et al., 2008). Fig.9 shows annual snowfall amounts and annual snowfall proportion distributions for 644
4 meteorological stations in China from 1960 to 1979, indicating that snowfalls are concentrated in the middle and
5 south-western Tibetan Plateau, northern Xinjiang province and north-eastern China. Statistical analysis indicates
6 that for more than 94% of stations, solid precipitation comprises less than 15% of the annual precipitation. Ren et
7 al. (2003) reported, that among the 2286 snowfall events, only 54 were blowing or drifting snow events
8 accounting for about 2.4% for 26 stations across China. Based on the regionalisation of snow drift in China,
9 blowing or drifting snow events occur mostly on the central and south-western Tibetan Plateau, in the northern
10 Xinjiang province and in north-eastern China (Wang and Zhang, 1999). In these regions, the $CSPG_{DFIR}$ should be
11 used as a reference gauge. In other regions, the $CSPG_{PIT}$ may be applicable. Based on the CMA snowfall and
12 snow depth data, and the regionalisation of snow drift in China, the applicable regions for the $CSPG_{PIT}$ and
13 $CSPG_{DFIR}$ as reference gauges are shown in Fig.10.

14 **Fig.8 about here**

15 **Fig.9 about here**

16 **Fig.10 about here**

17 **4.3 Limitations of this experiment**

18 Although the measurement procedures were based on the CMA's criteria, manual observations were infrequent,
19 and as a result, some precipitation events were summarised as single events, especially in the evenings. The
20 automatic meteorological tower could observe precipitation and wind speeds half-hourly during the precipitation
21 period, but the $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ were observed only twice per day. In this field
22 experiment, the precipitation phases were also distinguished by observers. This method is somewhat imprecise
23 although this has remained the traditional method since the 1950s at the CMA stations (CMA, 2007b).

24 The wind speeds at gauge height and the 10 m height were not observed directly but rather calculated from the
25 observed data at 1.5 m and 2.5m heights according to the Monin-Obukhov theory and the gradient method
26 (Eq.(8)). Although this method is widely used, it is effective only under neutral atmospheric conditions. For the
27 precipitation period from September 2012 to April 2015, the Z_0 was calculated using Eq. (9). The results showed
28 the Z_0 to be about 0.06m on average but it varied from nearly zero to 0.67m. As shown in Fig.11, in about 68.9%
29 and 95.1% of instances, the Z_0 was lower than 0.05 m and 0.25 m, respectively. In rare cases when the Z_0 was very

1 large, as shown in Fig.11, the Z_0 was arbitrarily assigned 1/2 of the grass height (h) at the site based on the
2 equation $Z_0=0.5hL_e$ provided by Lettau (1969). The very large Z_0 values usually appeared in late August and early
3 September when the vegetation coverage (L_e) was close to 100% at the Hulu watershed site.

4
5 **Fig. 11 about here**

6 **5 Conclusions**

7 The present experimental field study focused on wind-induced bias in precipitation measurements by CSPGs
8 specifically in a high mountain environment. The precipitation intercomparison experiment in the Hulu watershed
9 of the Qilian Mountains indicated that the $CSPG_{PIT}$ caught more rainfall, mixed precipitation and total
10 precipitation but less snowfall than the $CSPG_{DFIR}$. From most to least rainfall and mixed precipitation measured,
11 their ranking was $CSPG_{PIT} > CSPG_{DFIR} > CSPG_{SA} > CSPG_{UN}$, whereas in the snowy season, better wind shielding
12 increased the snow catch, leading to $CSPG_{DFIR} > CSPG_{PIT} > CSPG_{SA} > CSPG_{UN}$.

13 In regions with lower snowfall, such as the southern and central parts of China (Zhang and Zhong, 2014), and
14 in regions with a similar climate and environment to that of the Hulu watershed site, the $CSPG_{PIT}$ could be used as
15 a reference gauge because of its high catch ratio, simplicity and lower maintenance requirements. In north-eastern
16 China, northern Xinjiang province and the central and south-western Tibetan Plateau where snowfalls often occur,
17 the best choice of reference gauge would be the $CSPG_{PIT}$ for rainfall and the $CSPG_{DFIR}$ for snowfall observations.

18 The measured daily precipitation by shielded gauges increases linearly with that of unshielded gauges and is
19 independent of local environmental conditions. However, an increase in the ratio of the linear correlation should
20 depend on specific environmental conditions. For solid precipitation, some non-linear factors interfere with the
21 linear relationship to reduce the linear correlation coefficient.

22 The catch ratio vs. wind speed relationship for different precipitation types is simulated by cubic polynomials
23 and exponential functions. The $CR_{PIT/DFIR}$ does not have a significant relationship to wind speed, indicating that
24 both PIT and DFIR are effective in preventing wind from influencing the precipitation gauge catch. For daily rain
25 and mixed precipitation, the relationships are not statistically significant. Daily maximum and minimum
26 temperatures should reflect the atmospheric conditions of radiation and convection to some degree, and their
27 function in the CR vs. wind speed relationship needs further investigation in mountain environments. It is
28 recognised that in western China, the climatic and environmental conditions in the mountains vary both spatially
29 and temporally. To understand the similarities and differences among wind-induced biases in precipitation

1 measurements for the different mountain watersheds in western China, field experiments need to be carried out
2 continuously.

3 **Acknowledgments**

4 This paper was supported primarily by the National Basic Research Program of China (2013CBA01806) and
5 the National Natural Sciences Foundation of China (91025011, 41222001, 91225302 and 41401078).

6 **References**

- 7 Aaltonen, A., Elomaa, E., Tuominen, A., and Valkovuori, P.: Measurement of precipitation, in: Proceedings of the
8 Symposium on Precipitation and Evaporation, edited by: Sevruk, B. and Lapin, M., Slovak
9 Hydrometeorological Institute and Swiss Federal Institute of Technology, Bratislava, Slovakia, 42–46, 1993.
- 10 Bagnold, R. A.: *The Physics of Blown Sand and Desertdunes*, Methuen, New York, 85-95, 1941.
- 11 Charnes, A., Frome, E. L., and Yu, P. L.: The equivalence of generalized least squares and maximum likelihood
12 estimates in the exponential family, *Journal of the American Statistical Association*, 71: 169, 1976.
- 13 Che, T., Li, X., Jin, R., Armstrong, R., and Zhang T.: Snow depth derived from passive microwave remote-sensing
14 data in China, *Ann. Glaciol.*, 49, 145-154, 2008.
- 15 Chen, R., Song, Y., Kang, E., Han, C., Liu, J., Yang, Y., Qing, W., and Liu, Z.: A Cryosphere-Hydrology
16 observation system in a small alpine watershed in the Qilian Mountains of China and its meteorological
17 gradient, *Arct. Antarct. Alp. Res.*, 46(2): 505-523. doi: <http://dx.doi.org/10.1657/1938-4246-46.2.505>, 2014.
- 18 China Meteorological Administration (CMA): Specifications for surface meteorological observation Part 8:
19 Measurement of precipitation (QX/T 52-2007), China Meteorological Press, Beijing, 2007a.
- 20 China Meteorological Administration (CMA): Specifications for surface meteorological observation Part 4:
21 Observation of weather phenomenon (QX/T 48-2007), China Meteorological Press, Beijing, 2007b.
- 22 Ding, Y., Yang, D., Ye, B., and Wang, N.: Effects of bias correction on precipitation trend over China, *J. Geophys.*
23 *Res.*, 112, D13116, doi:10.1029/2006JD007938, 2007.
- 24 Dyer, A. J., and Bradley, E. F.: An alternative analysis of flux-gradient relationships at the 1976 ITCE, *Bound.-*
25 *Lay. Meteorol.*, 22, 3–19, doi: 10.1007/BF00128053, 1982.
- 26 Golubev, V. S.: On the problem of actual precipitation measurements at the observations site, in: Proceeding of the
27 International Workshop on the Correction of Precipitation Measurements WMO/TD 104, World

- 1 Meteorological Organization, Geneva, Switzerland, 61–64, 1985.
- 2 Goodison, B. E., Louie, B. P. Y. T., and Yang, D.: WMO solid precipitation measurement intercomparison: Final
3 report, Instrum. and Obs. Methods Rep. 67/Tech. Doc. 872, World Meteorol. Organ., Geneva, Switzerland,
4 1998.
- 5 IBM Corp: IBM SPSS Statistics for Windows, Version 19.0, IBM Corp, Armonk, NY, USA, 2010.
- 6 Lanza, L. G., Leroy, M., Alexandropoulos, C., Stagi, L., and Wauben, U.: WMO Laboratory Intercomparison of
7 Rainfall Intensity Gauges - Final Report, IOM Report No. 84, WMO/TD No. 1304, WMO, Geneva,
8 Switzerland, 2005.
- 9 Lettau, H.: Note on aerodynamic roughness-parameter estimation on the basis of roughness element description,
10 Journal of Applied Aerology, 8, 828-832, 1969.
- 11 Li, P.: Variation of snow water resources in northwestern China, 1951-1997, Sci. China Ser. D, 42, 73-79, 1999.
- 12 Li, X., Cheng, G., Jin, H., Kang, E., Che, T., Jin, R., Wu, L., Nan, Z., Wang, J., and Shen, Y.: Cryospheric change
13 in China, Global Planet. Change, 62, 210-218, doi:10.1016/j.gloplacha.2008.02.001, 2008.
- 14 Ma, Y., Zhang, Y., Yang, D., and Farhan, S.: Precipitation bias variability versus various gauges under different
15 climatic conditions over the Third Pole Environment (TPE) region, Int. J. Climatol., doi: 10.1002/joc.4045,
16 2014.
- 17 Metcalfe, J. R., and Goodison, B. E.: Correction of Canadian winter precipitation data. Preprints, in: Eighth Symp.
18 on Meteorological Observations and Instrumentation, Anaheim, CA, Am. Meteorol. Soc., 338–343, 1993.
- 19 Ren, Z., and Li, M.: Errors and correction of precipitation measurements in China, Adv. Atmos. Sci., 24, 449–458,
20 doi: 10.1007/s00376-007-0449-3, 2007.
- 21 Ren, Z., Wang, G., Zou, F., and Zhang, H.: The research of precipitation measurement errors in China, Acta
22 Meteorol. Sin., 61, 621-627, 2003.
- 23 Rodda, J. C.: Annotated Bibliography on Precipitation Measurement Instruments, WMO-No. 343, World Meteorol.
24 Org, Geneva., Switzerland, 1973.
- 25 Rodda, J. C.: The rainfall measurement problem, in: Proceedings of IAHS, General Assembly, Bern 1967,
26 Publication No. 78: 215-231, 1967.
- 27 Sevruk, B., and Hamon, W. R.: International comparison of national precipitation gauges with a reference pit gauge,

1 instruments and observing methods Rep., 17, 135, World Meteorol. Org., Geneva, 1984.

2 Sevruk, B., Ondrás, M., and Chvíla, B.: The WMO precipitation measurement intercomparisons, *Atmos. Res.*, 92,
3 376–380, doi:10.1016/j.atmosres.2009.01.016, 2009.

4 Snedecor, G., and Cochran, W.: *Statistical methods*. Iowa State University Press, Iowa, 1989.

5 Struzer, L. R.: Practicability analysis of rain gauge international comparison test results (in Russian). *Trans.*
6 *Voyeykov Main Geophys. Observ.*, 260, 77-94, 1971.

7 Sugiura, K., Yang, D., and Ohata, T.: Systematic error aspects of gauge-measured solid precipitation in the Arctic,
8 Barrow, Alaska, *Geophys. Res. Lett.*, 30, 1192, doi:10.1029/2002GL015547, 2003.

9 Tian, X., Dai, A., Yang, D., and Xie, Z.: Effects of precipitation-bias corrections on surface hydrology over
10 northern latitudes, *J. Geophys. Res.*, 112, D14101, doi:10.1029/2007JD008420, 2007.

11 Wang, Z., and Zhang, Z.: Regionalization of snow drift in China, *J. Mt. Sci.*, 17, 312-317, 1999.

12 Wolff, A. M., Nitu, R., Earle, M., Joe, P., Kochendorfer, J., Rasmussen, R., Reverdin, A., Sminth, C., Yang, D.,
13 and the SPICE-TEAM: WMO Solid Precipitation Intercomparison Experiment (SPICE): Report on the SPICE
14 Field Working Reference System for precipitation amount, WMO, IOM No. 116, TECO-2014, World
15 Meteorological Organization, Geneva, Switzerland, 2014.

16 Yang, D., Goodison, B. E., Metcalfe, J. R., Golubev, V. S., Elomaa, E., Gunther, T. H., Bates, R., Pangburn, T.,
17 Hanson, C. L., Emerson, D., Copaciu, V., and Milkovic, J.: Accuracy of Tretyakov precipitation gauge: Results
18 of WMO intercomparison, *Hydrol. Process.*, 9, 877– 895, doi:10.1002/hyp.3360090805, 1995.

19 Yang, D., Goodison, B. E., Metcalfe, J. R., Louie, P., Leavesley, G., Emerson, D., Hanson, C. L., Golubev, S. S.,
20 Elomaa, E., Gunthter, T., Pangburn, T., Kang, E., and Milkovic, J.: Quantification of precipitation
21 measurement discontinuity induced by wind shields on national gauges, *Water Resources Research*, 35, 491 –
22 508, doi: 10.1029/1998WR900042, 1999.

23 Yang, D., Metcalfe, J. R., Goodison, B. E., and Mekis, E.: An evaluation of Double-Fence Intercomparison
24 Reference (DFIR) gauge, in: *Proceedings of Eastern Snow Conference, 50th Meeting, Quebec, City*, 105–111,
25 1993.

26 Yang, D., Shi, Y., Kang, E., Zhang, Y., and Yang, X.: Results of solid precipitation measurement intercomparison
27 in the Alpine area of Urumqi River basin, *Chin. Sci. Bull.*, 36, 1105–1109, 1991.

- 1 Yang, D.: Double-Fence Intercomparison Reference (DFIR) vs. Bush Gauge for “true” snowfall measurement, *J.*
2 *Hydrol.*, 509, 94–100, doi:10.1016/j.jhydrol.2013.08.052, 2014.
- 3 Yang, D.: Research on analysis and correction of systematic errors in precipitation measurement in Urumqi River
4 basin, Tianshan, PhD thesis, Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences,
5 Lanzhou, China, 169 pp., 1988.
- 6 Ye, B., Yang, D., and Ma, L.: Effect of precipitation bias correction on water budget calculation in Upper
7 YellowRiver, China, *Environ. Res. Lett.*, 7, 025201, doi:10.1088/1748-9326/7/2/025201, 2012.
- 8 Ye, B., Yang, D., Ding, Y., and Han, T.: A bias-corrected precipitation climatology for China. *Acta Geogr. Sin.*, 62,
9 3-13, 2007.
- 10 Ye, B., Yang, D., Ding, Y., Han, T., and Koike, T.: A bias-corrected precipitation climatology for China, *J.*
11 *Hydrometeorol.*, 5, 1147–1160, doi: <http://dx.doi.org/10.1175/JHM-366.1>, 2004.
- 12 Zhang, T., and Zhong, X.: Classification and regionalization of the seasonal snow cover across the Eurasian
13 Continent, *J. Glaciol. .Geocryol.*, 36, 481-490, 2014.
- 14 Zhang, Y., Ohata, T., Yang, D., and Davaa, G.: Bias correction of daily precipitation measurements for Mongolia,
15 *Hydrol. Process.*, 18, 2991–3005, doi: 10.1002/hyp.5745, 2004.

16

17

18

1
2
3
4
5
6
7
8
9
10
11
12
13
14

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 (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 (°C)	-12.4	-7.7	-4.4	2.2	7.0	11.2	12.5	12.1	8.0	1.4	-5.6	-11.3	1.1
Monthly mean daily maximum air temperature (°C)	-4.0	0.7	3.5	10.3	14.3	18.2	19.5	19.7	15.4	10.2	3.6	-1.9	9.1
Monthly mean daily minimum air temperature (°C)	-19.0	-14.8	-11.6	-5.2	0.6	4.9	6.8	5.8	1.8	-5.5	-12.7	-18.2	-5.6
Monthly mean wind speed at the 1.5m height (m s ⁻¹)	1.79	1.96	2.30	2.55	2.42	1.98	1.82	1.81	1.93	1.81	2.08	1.96	2.03
Monthly mean wind speed at the 2.5m height (m s ⁻¹)	1.79	2.02	2.43	2.77	2.65	2.16	2.04	2.02	2.16	1.99	2.19	2.01	2.18
Monthly potential evaporation (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 the Qilian Mountains.

Gauge	Abbreviation	Size(φ denotes orifice diameter and h is observation height)	Start date	End date	Observation time
Unshielded China standard precipitation gauge (CMA, 2007a)	CSPG _{UN}	$\varphi=20\text{cm}, h=70\text{cm}$	Jun 2009	Apr, 2015	20:00 and 08:00, Local time
Single Alter shield (Struzer, 1971) around a CSPG	CSPG _{SA}	$\varphi=20\text{cm}, h=70\text{cm}$	Jun 2009	Apr, 2015	20:00 and 08:00, Local time
A CSPG in a Pit (Sevruk and Hamon, 1984)	CSPG _{PIT}	$\varphi=20\text{cm}, h=0\text{cm}$	Sep 2010	Apr, 2015	20:00 and 08:00, Local time
DFIR shield(Goodison et al., 1998) around a CSPG	CSPG _{DFIR}	$\varphi=20\text{cm}, h=3.0\text{m}$	Sep 2012	Apr, 2015	20:00 and 08:00, Local time

1

2

3 **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	$100 \left(\frac{\text{CSPG}_{\text{SA}}}{\text{CSPG}_{\text{UN}}} - 1 \right)$	$100 \left(\frac{\text{CSPG}_{\text{PIT}}}{\text{CSPG}_{\text{UN}}} - 1 \right)$	$100 \left(\frac{\text{CSPG}_{\text{DFIR}}}{\text{CSPG}_{\text{UN}}} - 1 \right)$	CSPG _{SA} (mm)	CR	$100 \left(\frac{\text{CSPG}_{\text{PIT}}}{\text{CSPG}_{\text{SA}}} - 1 \right)$	$100 \left(\frac{\text{CSPG}_{\text{DFIR}}}{\text{CSPG}_{\text{SA}}} - 1 \right)$	CSPG _{PIT} (mm)	CR	$100 \left(\frac{\text{CSPG}_{\text{DFIR}}}{\text{CSPG}_{\text{PIT}}} - 1 \right)$	CSPG _{DFIR} (mm)	CR
Sep 2010-	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			
Apr 2015	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-	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
Apr 2015	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

4

5

1
2
3
4
5
6
7
8
9
10
11
12

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

Temporal scale	Phase	Gauges	Catch ratio (CR) vs. wind speed relationships*	<i>P</i> (mm)	No. of events	F-test
Precipitation event	Rain	CSPG _{UN}	$CR_{UN/DFIR,Rain} = 0.181W_{s10}^3 - 0.256W_{s10}^2 - 0.795W_{s10} + 100$ $R^2=0.042$	<i>P</i> >3.0	103	$\alpha=0.23$
		CSPG _{SA}	$CR_{SA/DFIR,Rain} = 0.188W_{s10}^3 - 0.719W_{s10}^2 + 0.551W_{s10} + 100$ $R^2=0.083$			$\alpha=0.03$
		CSPG _{PIT}	$CR_{PIT/DFIR,Rain} = 0.150W_{s10}^3 - 0.425W_{s10}^2 + 1.119W_{s10} + 100$ $R^2=0.008$			$\alpha=0.83$
	Mixed	CSPG _{UN}	$CR_{UN/DFIR,Mixed} = 100e^{-0.06W_{s10}}$ $R^2=0.194$	<i>P</i> >1.0	24	$\alpha=0.07$
		CSPG _{SA}	$CR_{SA/DFIR,Mixed} = 100e^{-0.04W_{s10}}$ $R^2=0.100$			$\alpha=0.16$
		CSPG _{PIT}	$CR_{PIT/DFIR,Mixed} = 100e^{-7E-07W_{s10}}$ $R^2=0.000$			$\alpha=no\ data$
	Snow	CSPG _{UN}	$CR_{UN/DFIR,Snow} = 100e^{-0.08W_{s10}}$ $R^2=0.412$	<i>P</i> >1.0	34	$\alpha=6.4E-05$
		CSPG _{SA}	$CR_{SA/DFIR,Snow} = 100W_{s10}^{-0.02}$ $R^2=0.090$			$\alpha=0.07$
		CSPG _{PIT}	$CR_{PIT/DFIR,Snow} = 100e^{-0.01W_{s10}}$ $R^2=0.024$			$\alpha=0.35$
Daily precipitation	Rain	CSPG _{UN}	$CR_{UN/DFIR,Rain} = -1.400W_{s0.7}^3 + 2.987W_{s0.7}^2 - 6.116W_{s0.7} + 100$ $R^2=0.032$	<i>P</i> >3.0	90	$\alpha=0.37$
		CSPG _{SA}	$CR_{SA/DFIR,Rain} = -0.924W_{s0.7}^3 + 1.158W_{s0.7}^2 - 3.338W_{s0.7} + 100$ $R^2=0.021$			$\alpha=0.55$
		CSPG _{PIT}	$CR_{PIT/DFIR,Rain} = -0.952W_{s0.7}^3 - 1.503W_{s0.7}^2 + 2.237W_{s0.7} + 100$ $R^2=-0.00$			$\alpha=no\ data$
	Mixed	CSPG _{UN}	$CR_{UN/DFIR,Mixed} = 100e^{-0.12W_{s0.7}}$ $R^2=0.144$	<i>P</i> >1.0	21	$\alpha=0.09$
		CSPG _{SA}	$CR_{SA/DFIR,Mixed} = 100e^{-0.07W_{s0.7}}$ $R^2=0.094$			$\alpha=0.18$
		CSPG _{PIT}	$CR_{PIT/DFIR,Mixed} = 100e^{-0.001W_{s0.7}}$ $R^2=0.003$			$\alpha=no\ data$
	Snow	CSPG _{UN}	$CR_{UN/DFIR,Snow} = 100e^{-0.11W_{s0.7}}$ $R^2=0.477$	<i>P</i> >1.0	27	$\alpha=1.8E-04$
		CSPG _{SA}	$CR_{SA/DFIR,Snow} = 100e^{-0.03W_{s0.7}}$ $R^2=0.087$			$\alpha=0.14$
		CSPG _{PIT}	$CR_{PIT/DFIR,Snow} = 100e^{-0.01W_{s0.7}}$ $R^2=-0.00$			$\alpha=no\ data$

*: 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).

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36

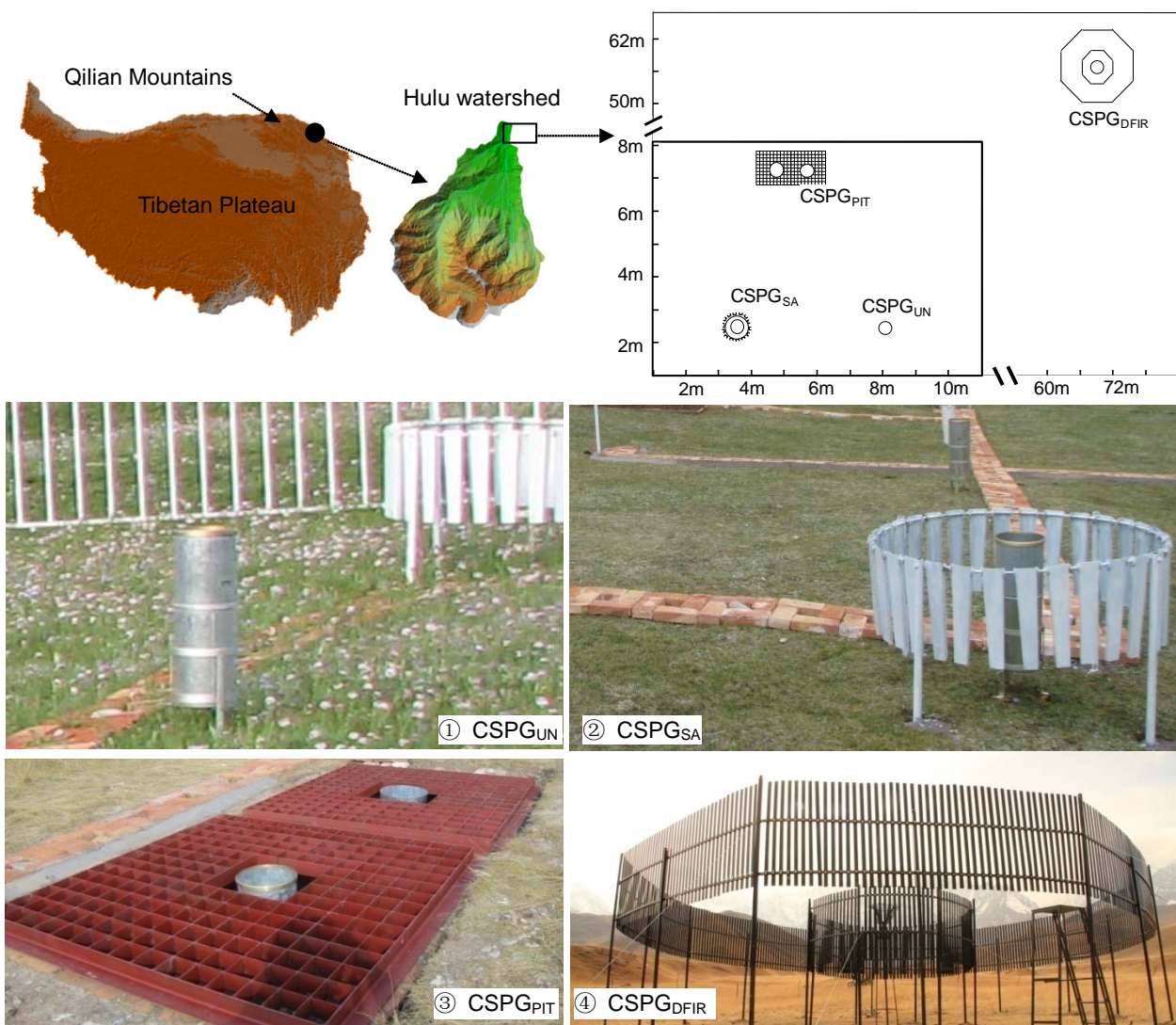
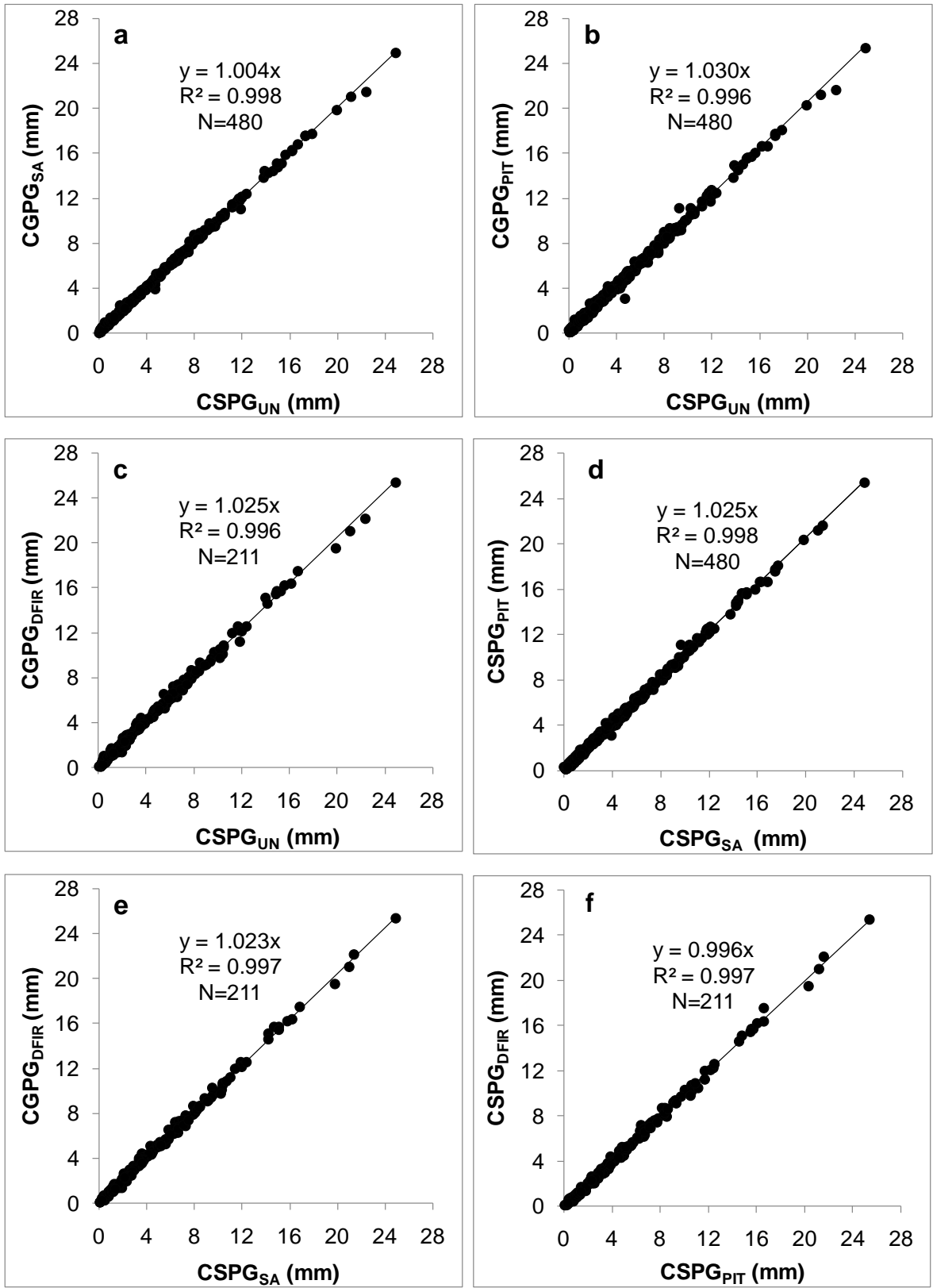


Figure 1. Precipitation gauge intercomparison experiment in the Qilian Mountains, Tibetan Plateau.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27



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

30

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

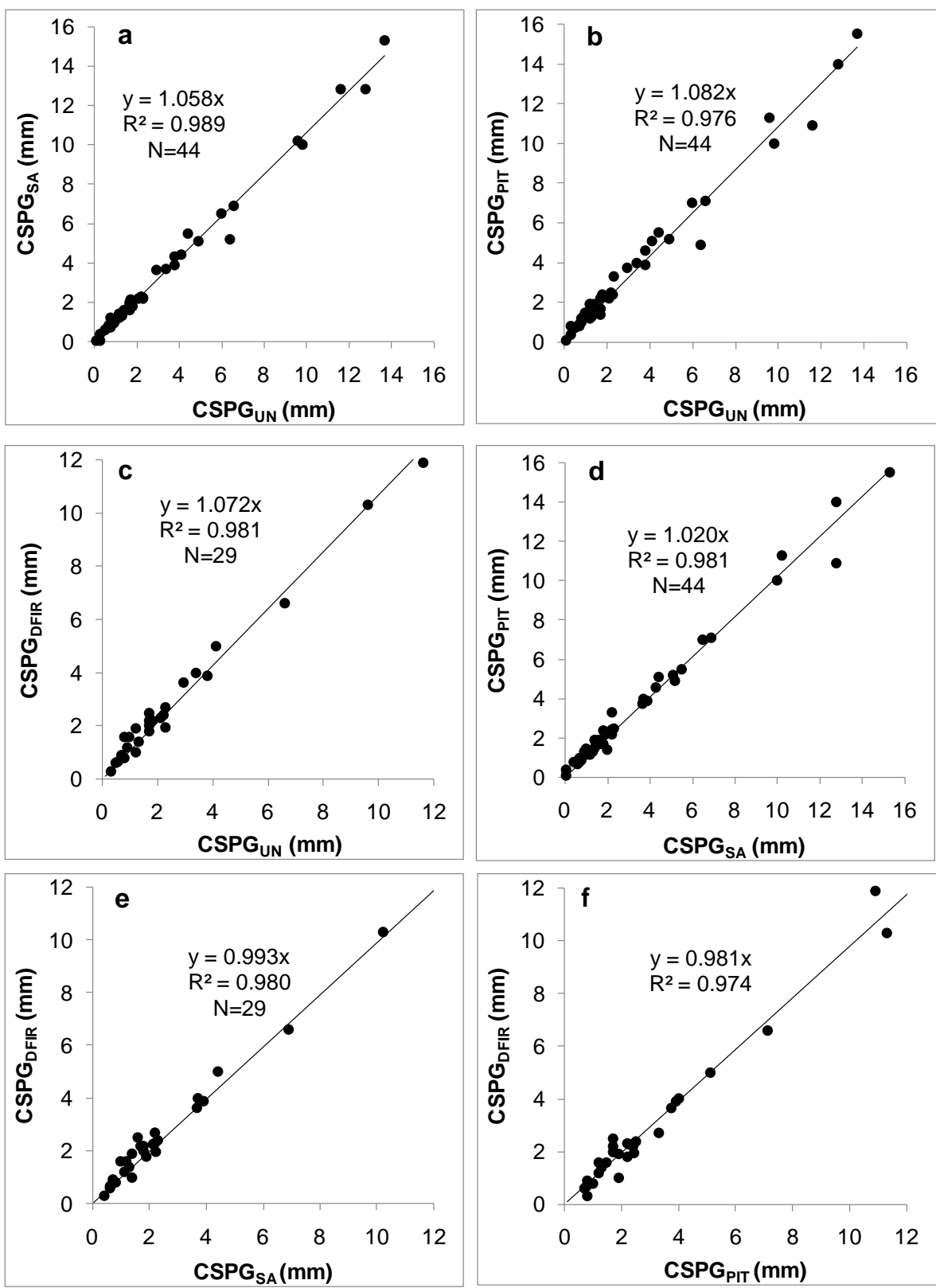
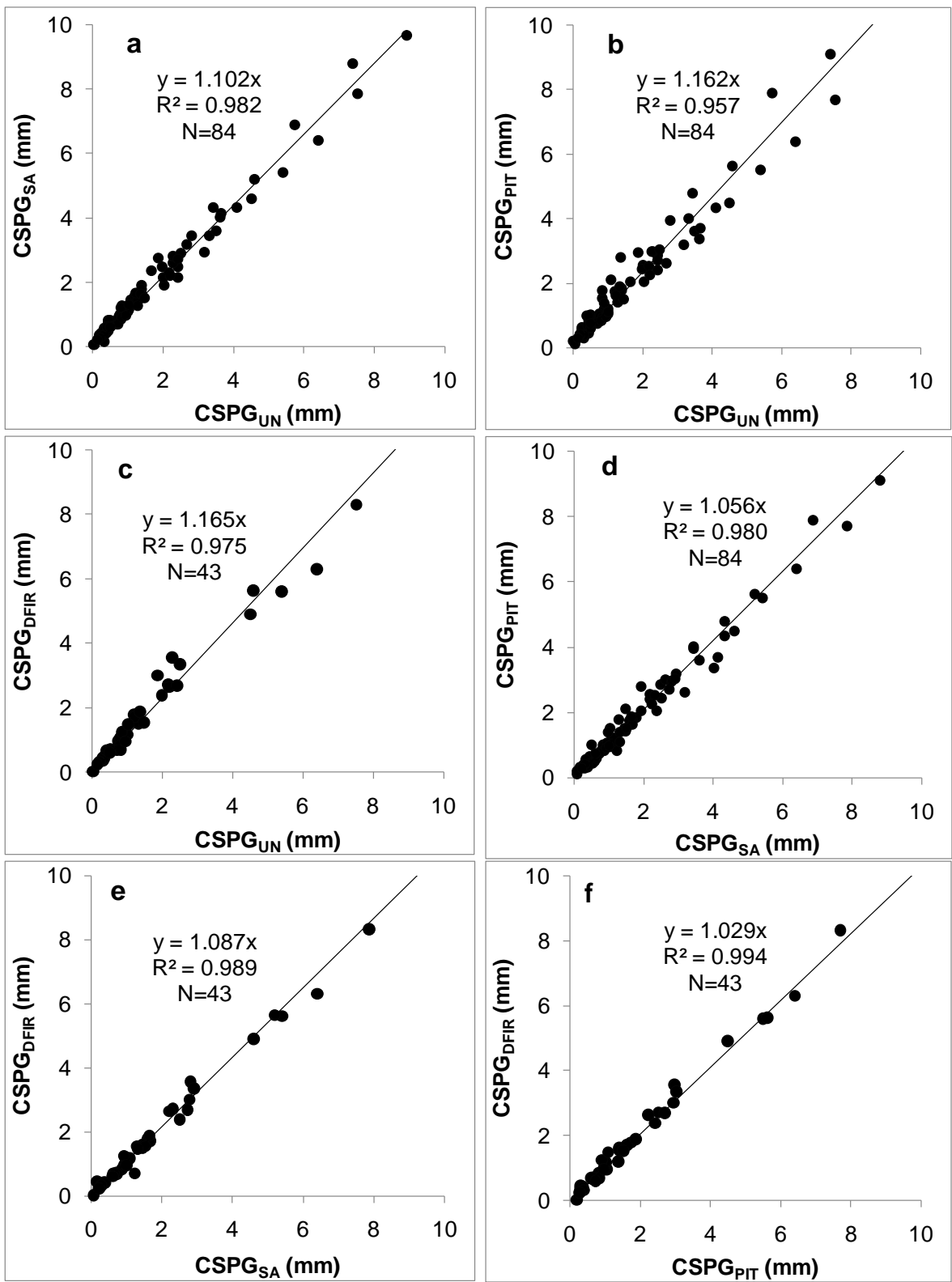


Figure 3. Intercomparison plots among CSPG_{UN}, CSPG_{SA}, CSPG_{PIT} and CSPG_{DFIR} for the mixed precipitation events from September 2010 (a, b and d) and September 2012 (c, e and f) to April 2015.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22



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

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

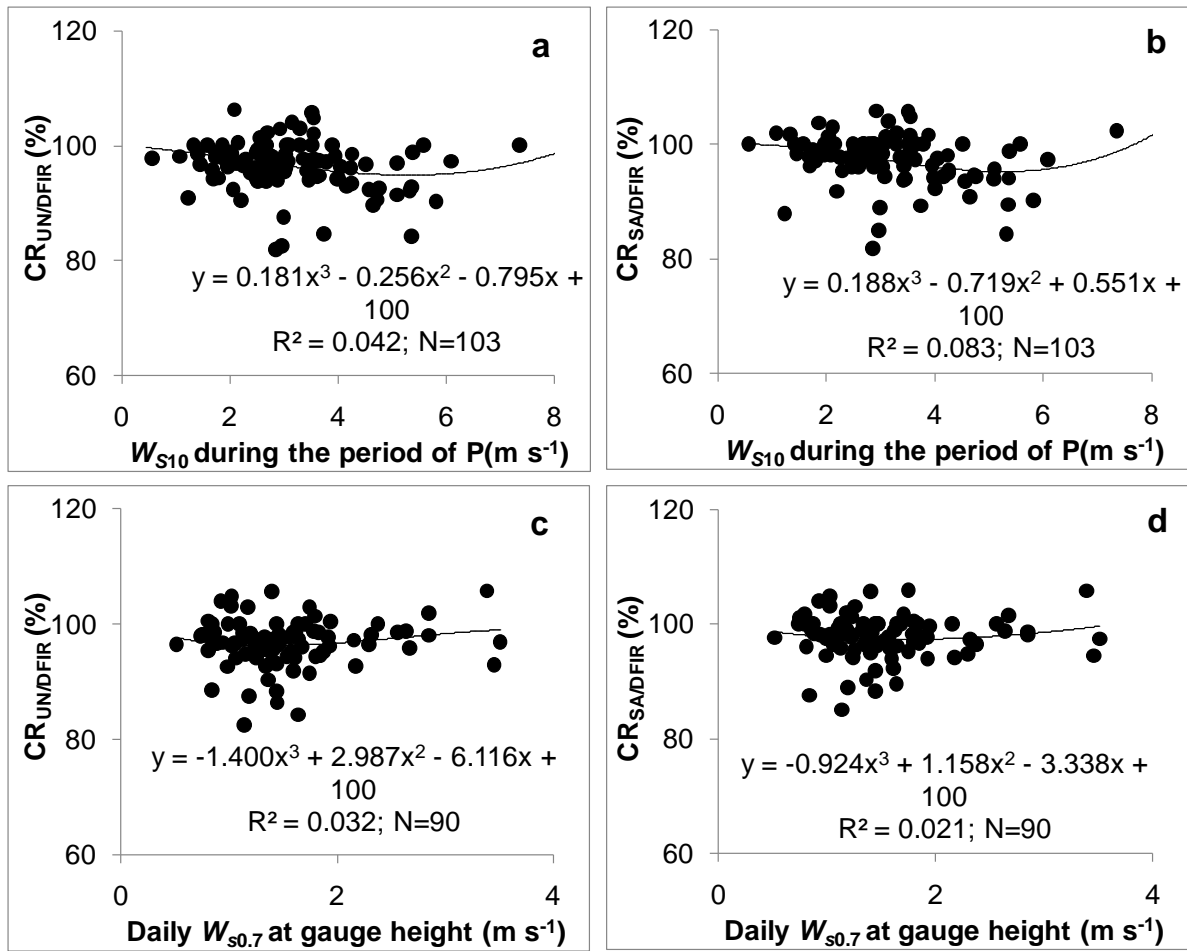


Figure 5. Catch ratios (CRs) vs. wind speed for rainfall events (a and b) and daily rainfall (c and d) greater than 3.0 mm.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30

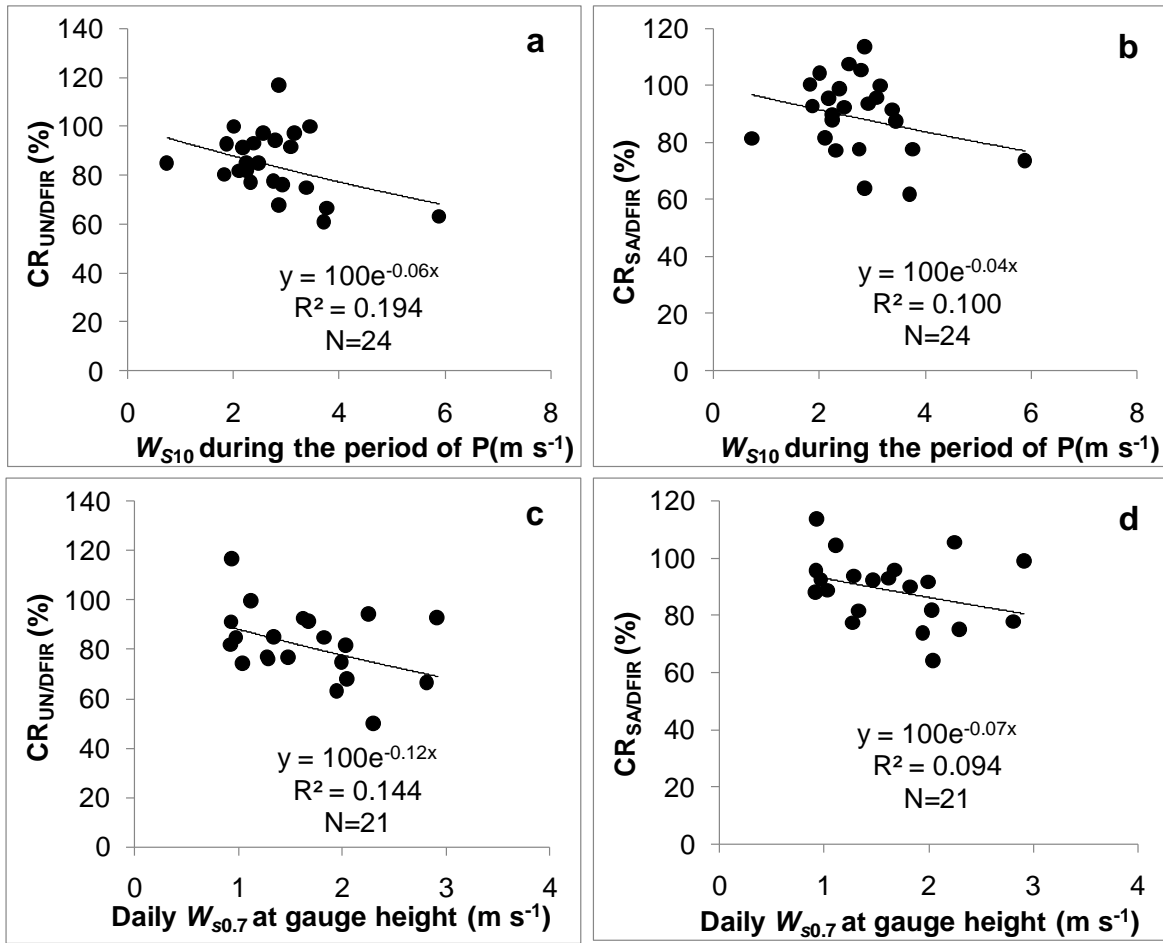


Figure 6. Catch ratios (CRs) vs. wind speed for mixed precipitation events (a and b) and daily mixed precipitation (c and d) greater than 1.0 mm.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30

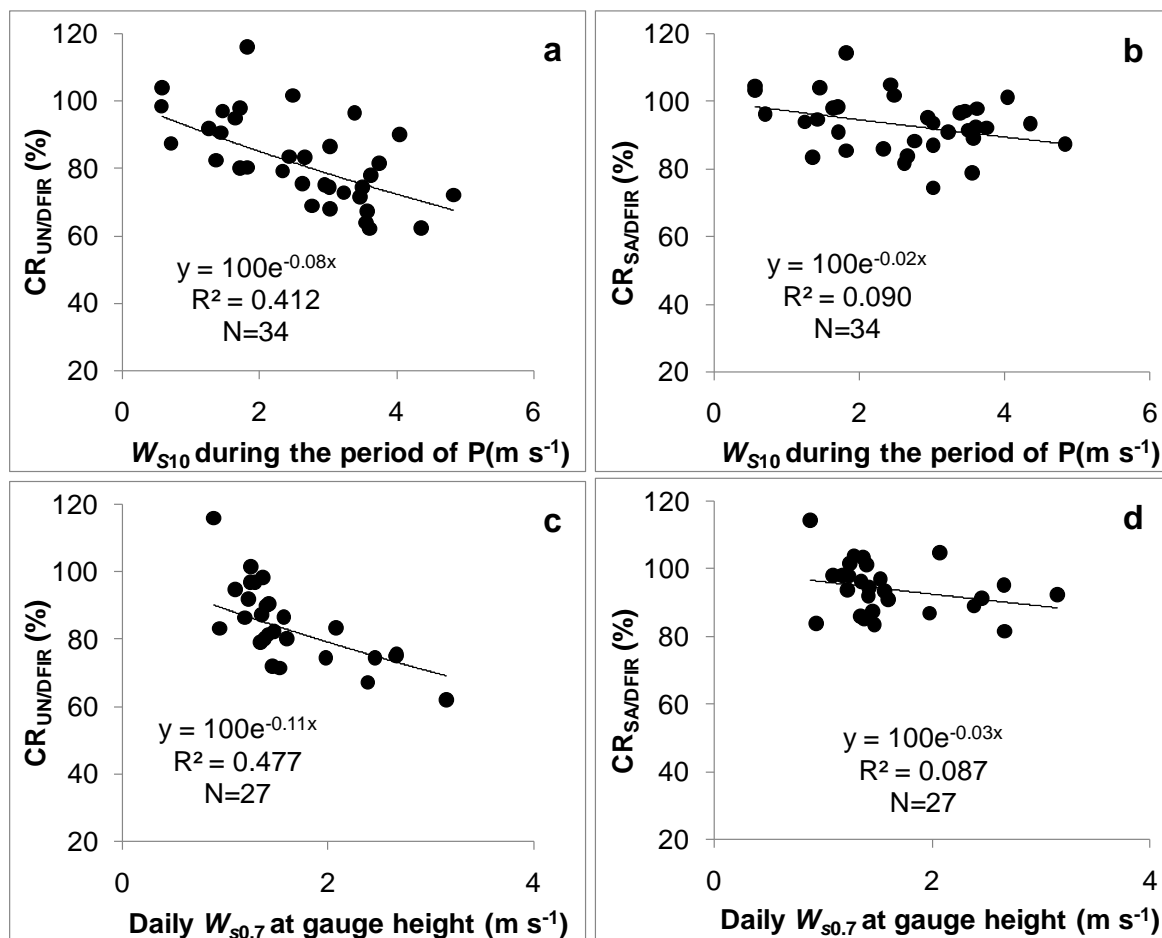


Figure 7. Catch ratios (CRs) vs. wind speed for the snowfall event (a and b) and the daily (c and d) snowfall greater than 1.0 mm.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30

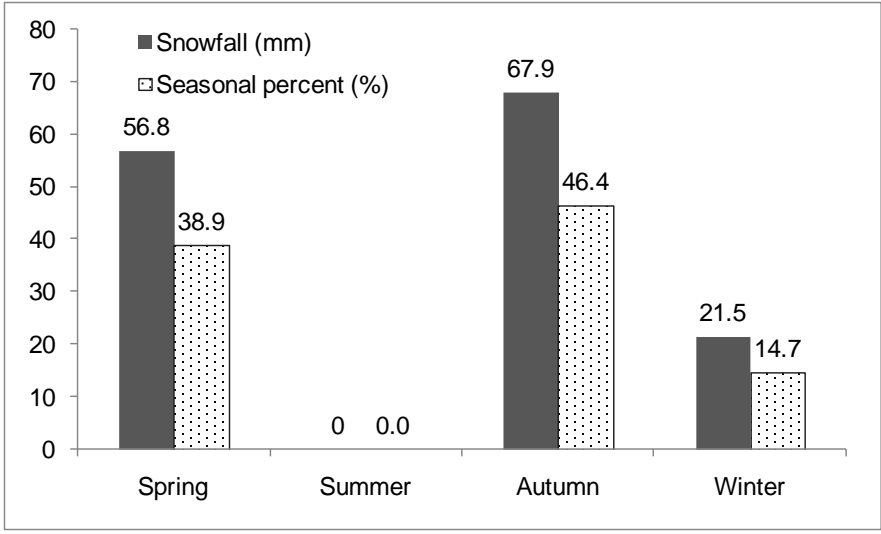


Figure 8. Seasonal snowfall and its percentage from September 2010 to April 2015 at the Hulu watershed site.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

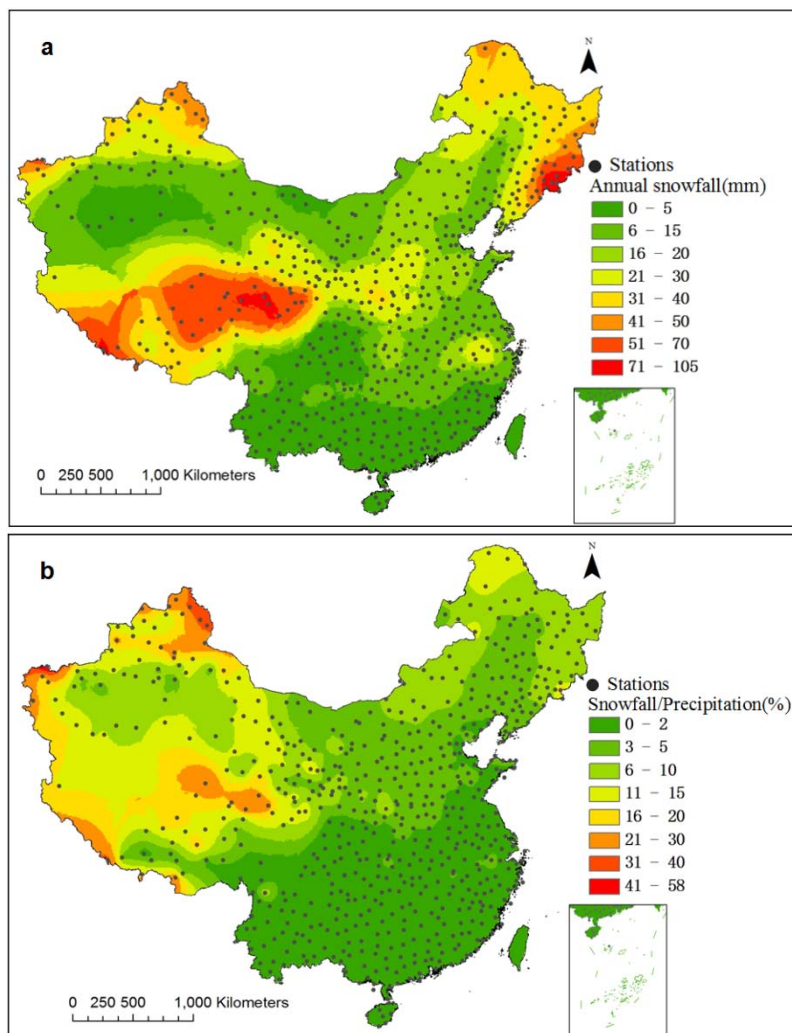


Figure 9. (a) Annual snowfall (mm) and **(b)** ratio of annual snowfall to total precipitation in China.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

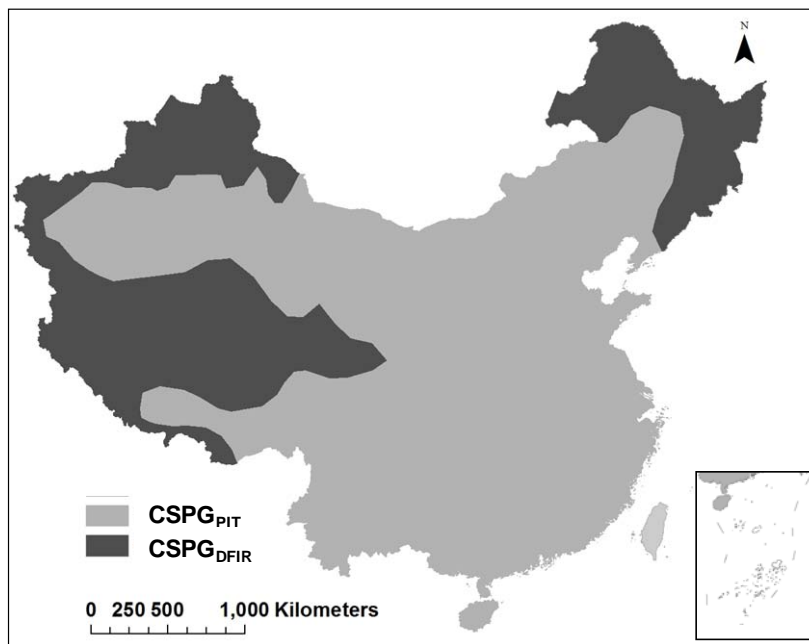


Figure 10. Applicable regions in China for the $CSPG_{PIT}$ and $CSPG_{DFIR}$ as reference gauges.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21

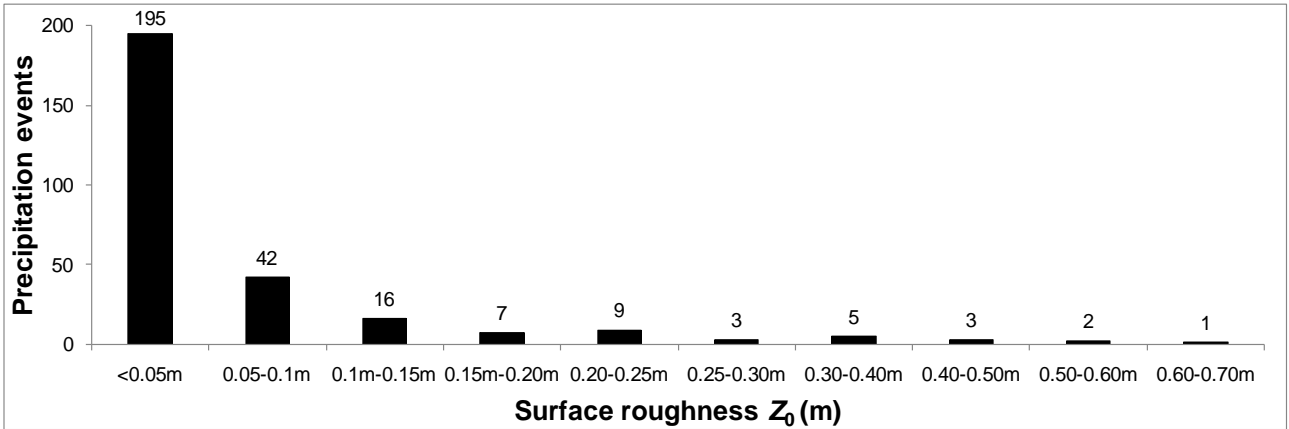


Figure 11. Surface roughness during the precipitation period from September 2012 to April 2015.