Interactive comment on “Precipitation measurement intercomparison in the Qilian Mountains, Northeastern Tibetan Plateau” by R. Chen et al.

Anonymous Referee #3

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1. General comments

The discussion paper ‘Precipitation measurement intercomparison in the Qilian Mountains, Northeastern Tibetan Plateau,’ by R. Chen et al., presents analysis of manual precipitation measurements using a Chinese standard precipitation gauge (CSPG) in various configurations. The analysis covers four years of measurements using the CSPG in unshielded, single-Alter shield, and pit configurations. Measurements during the last two years were also obtained using a CSPG in a Double-Fence Intercomparison Reference (DFIR) shield, which is the World Meteorological Organization (WMO) recommended reference configuration for snowfall measurements.

Scatter plots comparing measurements from different configurations indicated that the pit and DFIR configurations performed comparably for mixed and solid precipitation, suggesting that the pit configuration could be a viable option for a reference configuration for these precipitation types in similar environments. The pit configuration is a lower-cost option than the DFIR, so this is an important result for operational networks in regions with limited annual snow cover and blowing snow.

Additional plots investigated the influence of wind speed on the catch ratios of precipitation measured by a given configuration to that measured by a reference configuration for events in different precipitation regimes (liquid, mixed, solid). Linear fits to these plots were used to develop equations that could be used to ‘adjust’ measurements in non-reference configurations for the influence of wind. While these plots certainly provide insight into the catch ratio-wind speed relationships for different configurations and precipitation types, the small number of events and apparent poor fit quality do not impart a high degree of confidence in the use of the resulting equations for adjusting precipitation observations.

Overall, the authors make good use of tables and figures to convey results and analysis that can be a bit cumbersome to follow in the text. The background information and discussion are presented well, but the paper would benefit from some additional description of methods (as discussed further in the Specific Comments, below). The applicability of the findings to operational networks, albeit to a limited number of stations with specific conditions, is the main strength of this paper, and warrants publication for broader distribution and implementation. The broader applicability of the adjustment equations, however, is questionable, and careful consideration should be given to how these are presented in the manuscript.

Answer: Thank you very much for your detailed advices. We have updated the data to **April 30 2015**, and now there are total 608 precipitation events from September 2010 to April 2015 and 283 events during September 2012 to April 2015. According to the advices of the former two Reviewers, the paper has been majorly revised.

After revision, the adjustment equations have been carefully considered. Please see Table 4 and other equations in the text.

The new version after your advices is uploaded this time. It is the least version (Version 2), but it is not the last version. Because I received two Reviewer's comments on the same day June 4 2015, but this discussion would be closed on June 5, thus this revised Version 2 was not perfect. We will upload Version 3 tonight.

2. Specific comments

a. Abstract and Introduction

As identified by Reviewer 1, this study focusses on the analysis of the same precipitation gauge in different configurations, rather than different ‘precipitation gauges,’ as indicated in the text. The wording and gauge configuration nomenclature proposed by Reviewer 1 should be implemented to help address this issue throughout the paper. When stating catch ratios in the abstract, it is important to note which configuration is being used as the reference (i.e. the denominator when computing catch ratios).

Answer: This kind of problem has been revised in the new version. Thank you very much. $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ have been used. The nomenclature 'catch ratio' is wrongly used before in the abstract and in some text.

b. Data and methods

When taking the manual observations, are any additional measures taken if there is frost on the collector, or if there is solid precipitation accumulated on the rim of the collector?

Answer: The measurements are based on the criterion published by China Meteorological Administration (CMA). In the cold season, the rain collector and glass bottle are removed from the CSPG. Instead, it use the solid precipitation (P) collector. There are two choices according to the CMA's criterion. We use the second one. That is, when there is solid P, anther snow collector is used to replace the present using one, and the using one is weighted by an electronicbalance with high accuracy (0.1g or 0.003mm).

If there is frost on the outer wall of the collector, it will be removed by using a dry hand towel. If there is solid P on the rim of the collector, half of them (semi circular) will be removed and then the collector is weighted. However, this phenomenon little happens because the rime of the CSPG is well designed. We would add these words in **the text as:' If there is frost on the collector, it will be wiped up by using a dry hand towel. In rare cases of snowfall accumulating on the rim of the collector, half of them (semi circular) will be removed before they are weighted.** '.

Is the precipitation measured by the DFIR configuration used to calculate the adjusted accumulation in Equation (1) when the Pit gauge is used as the reference?

Answer: In the revised version, the only reference is the DFIR shield around a CSPG ($CSPG_{DFIR}$) when the catch ratio is calculated (except in part of Table 1).

What is the frequency of each type of observation (precipitation, wind speed, temperature)?

Answer: each type of observation in the meteorological tower is observed every 30 seconds, and they are saved every half an hour (mean or sum). The following sentences are added: 'They are observed every 30 seconds and are saved as half-hourly values (sum or mean).'

This is important in terms of how representative the conditions are for each measurement.

Answer: Thank you. This kind of description will be added.

c. Results

As indicated by Reviewer 2, the details of phase discrimination are critical, and must be included in the manuscript.

With the method of phase discrimination used, how representative is the phase for each measurement? How can you be sure, for example, that a certain event was only snow, and not some combination of snow with mixed precipitation, ice pellets, etc.?

Answer: As we know, the best method to classify the P type is measured directly by using instrument such as raindrop spectrograph, double-polarization radar Doppler, etc. But we have not such instruments at our site. The traditional method is distinguished manually. This method is described in detail in the CMA's criterion. Though this method is some rough, it is used at the CMA's stations all over China in the past 50-60 years. Therefore, it is also used at out site. Surely this kind of observation is not satisfactory.

The present methods of phase discrimination have been reported in the literatures, and we will cite and describe them in the paper. But this kind of method is not better than the manual observation method for CSPG in China: 1) its accuracy is not higher than manual observation; 2) their reference data are still P phase data measured manually at the CMA's stations (distinguished by observer's eyes); 3) the used air temperature, dew point or wet bulb temperature of the present phase classification method is the average just before precipitation, during precipitation, or daily? The parameter of this kind of method also varied spatially.

The following paragraph is added in the text: ' 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. For the CSPG, there are several methods of phase discrimination, 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 method vary largely in spatial, and their reference precipitation phase data are still from the CMA's stations. '

In Section 3.1, why is the reference changed for the 2012-2014 rainfall observations? Would it not make more sense to use the same reference (pit) for all rainfall events?

Answer: According to the Reviewer 1's advice, the only reference for all P phase is $CSPG_{DFIR}$. In the revised version, we just compare the CSPG with different shields. Now who is reference is not so important, because they are all intercompared.

On P. 2208, lines 5-6, you note that 'comparative studies indicate that the Pit gauge CR is superior to that of the DFIR or the other gauges (Fig. 2)'. How is this clear from Fig. 2? I see a near 1:1 relationship between the Pit and DFIR configurations, and no comparison plots are shown for the CSPG and Alter relative to the DFIR.

Answer: this note is based on the rainfall amounts, because the $CSPG_{PIT}$ measures more P than the $CSPG_{DFIR}$. It may be not reasonable. Thus in the revised version, we have deleted all these kinds of conclusions.

Given the potential for spatial variability in falling precipitation, are the differences among the different configurations significant in rain? Is the Pit configuration really 'superior' if the maximum difference is less than 5%? What is the estimated uncertainty for the manual observations?

Answer: All these kinds of statements are deleted in the revised version.

In Section 3.2, the Pit configuration catches about 2.5% more mixed precipitation than DFIR – is this significant?

Answer: All these kinds of statements are deleted in the revised version.

d. Catch ratio vs. wind speed (Section 3.4)

When fitting the data, were any other curve types tried (besides linear)? The R2 values throughout suggest poor fit quality. These poor fits could result, at least in part, from the lower threshold accumulation for precipitation events (1 mm) relative to previous studies (3 mm).

Answer: The best fitting curve types have been used after the new data are added in the revised version (**Table 4 and some equations**). Most of them are not linear. Their reliability is tested by using F-test method.

For rainfall, precipitation events or daily P greater than 3.0mm are chosen, but for snowfall and mixed, the critical value of 1.0mm is used because there is few event greater than 3.0mm.

I recommend referring to the application of the equations as ‘adjustments’ rather than ‘calibrations.’

Answer: Ok. Total 12 'calibrations' are replaced.

Given the limited number of points and poor fit quality, would you recommend using these equations for adjusting precipitation measurements from a CSPG in unshielded or single-Alter configurations? I think that these results can be presented with the objective of illustrating general trends, but I question the applicability of the resulting adjustment equations, and whether they should be presented with this purpose in mind.

Answer: The new equations are tested by using F-test method. The data are updated to April 30 2015, the results would be improved now.

There is so much scatter in Fig. 8a that I don’t think you can say that the ‘Pit/DFIR CR is approximately 1’ (P. 2210, lines 16-18). This statement is based on a linear fit with a very low R2 value.

Answer: All these kinds of statements are deleted in the revised version. The figures are redrawn after data updated.

Also for Fig. 8a – given the scatter observed, one cannot really state with confidence that ‘wind speed has little effect’ (P. 2210, line 17).

Answer: The confidence is added by using F-test in Table 4 in the new revised version (data are updated to April 30 2015.).

For Fig. 8c, the magnitude of the slope is larger than for Alter/DFIR CR in Fig. 8b, yet it is stated that 'wind speed has no significant effect on Pit/DFIR CR' (P. 2211, line 10).

Answer: They are revised.

The scatter in values from about 0.8 to 1.2 should also be noted.

Answer: ok.

3. Proposed technical corrections

P. 2203, line 3: add comma after 'sytematic errors'

Answer: ok.

P. 2203, line 5: change 'It would affect' to 'These errors affect'

Answer: ok.

P. 2203, line 8: change 'an UK' to a 'UK'

Answer: ok.

P.2203, line 15: change 'Reference (DFIR) with a shielded Tretyakov gauge' to 'Reference (DFIR) shield with a manual Tretyakov gauge'

Answer: ok.

P.2203, line 16: change 'standard snow gauges' to 'standard snow gauge configuration'

Answer: ok.

P.2203, lines 19-20: 'Considering the automation of precipitation measurements' – this statement is unclear; please elaborate.

Answer: ok. It is revised as: ' Because automation of precipitation measurements are widespread '.

P.2203, lines 24-25: The WMO-SPICE project employs several different reference configurations, not just automatic gauges in the DFIR shield (see, for example, the report from the second session of the SPICE-IOC: http://www.wmo.int/pages/prog/www/IMOP/reports/2012/IOC-SPICE-2.pdf).

Answer: It is revised as: 'the WMO-SPICE project still selected DFIR shield as part of the reference configurations.'

P. 2204, line 5: change 'precipitation is concentrated in warm season' to 'precipitation occurs most frequently during the warm season'

Answer: ok.

P. 2204, line 3: change to 'The DFIR shield has been operated as part of reference configurations at 25 stations: : :' and please apply this type of terminology throughout

Answer: ok.

P. 2204, line 6: change to 'in the valley site'

Answer: ok.

P. 2204, line 9: change to 'at the open Daxigou Meteorological Station'

Answer: ok.

P. 2204, line 12: change to 'for the CSPG'

Answer: ok.

P. 2204, lines 13-14: change 'neighborhood' to 'neighboring'

Answer: ok.

P. 2204, line 14: change to 'accurate precipitation data are urgently needed'

Answer: ok.

P. 2204, line 15: change to 'conducted in or reported from'

Answer: ok. This sentence has been deleted in the new version, and now it don't need revise.

P. 2204, line 16: change 'around regions' to 'surrounding regions'

Answer: ok. This sentence has been deleted in the new version and now it don't need revise.

P. 2204, line 16: change 'here it presents four-years gauge intercomparison experiment'to 'we present a four-year Intercomparison experiment'.

Answer: ok.

P. 2204, line 23: change to 'Alter shield (Alter) was selected as another Intercomparison configuration for the present study'

Answer: ok.

P. 2204, line 28: change to 'rarely exceed 10 cm in most parts of China'

Answer: ok. This sentence has been deleted in the new version and now it don't need revise.

P. 2205, line 1: Pit and DFIR catch ratios relative to which reference?

Answer: This part has been revised according to the Reviewer 1's advices.

P. 2205, line 3: add comma after ‘wind speeds’

Answer: ok. This sentence has been deleted in the new version and now it don't need revise.

P. 2205, lines 7-8: change to ‘mountains, on the northeastern edge of the Tibet plateau’

Answer: ok.

P. 2205, line 10: change to ‘and is concentrated during the warm season’

Answer: ok.

P. 2205, line 20: change ‘Alter shelter’ to ‘Alter shield;’ apply this change throughout the manuscript

Answer: ok. It has been revised throughout the manuscript according to the Reviewer 1's advices.

P. 2205, line 22: change to ‘a Double Fence Intercomparison Reference shield with a Tretyakov-shielded CSPG’

Answer: ok.

P. 2205, line 24: add comma after ‘precipitation events’, and add ‘the’ between ‘in’ and ‘warm season’

Answer: ok.

P. 2206, line 2: add comma after ‘warm season’

Answer: ok.

P. 2206, line 7: change to ‘is the wetting loss’ and ‘is the evaporation loss’

Answer: ok.

P. 2206, line 10: remove ‘and’ preceding ‘0.30 mm’

Answer: ok.

P. 2206, line 12: change to ‘value smaller than the other losses’

Answer: ok.

P. 2206, line 17: change to ‘number of trace observations per day’

Answer: ok.

P. 2206, line 18: change to ‘The most important factor’

Answer: ok.

P. 2207, line 10: change to ‘This field experiment focusses on two key aspects.’

Answer: ok.

P. 2207, lines 10-11: change ‘observations comparisons’ to ‘observation comparisons’

Answer: ok.

P. 2207, line 17: change to ‘a total of 578 precipitation observations were recorded’

Answer: ok.

P. 2207, lines 18-19: change ‘happened’ to ‘occurred’ each time

Answer: ok. A total of 8 'happened' are replaced.

P. 2207, line 25: change to ‘was selected as the reference configuration for rainfall events, and 479 events’

Answer: This sentence is deleted in the new version.

Fig. 2: text indicates these data are from Sept. 2012 to Sept. 2014, while caption indicates Sept. 2010 to Sept. 2014. Which data are plotted here?

Answer: In the original Fig.2a and Fig.2b, the data are from Sept. 2010 to Sept. 2014, whereas in the Fig.2c, it is from Sept. 2010 to Sept. 2014. In the text, it compares the CSPGPIT and CSPGDFIR. Thus, data only can be compared from Sept. 2010 to Sept. 2014.

In the new revised version, this question has been revised in the whole manuscript.

P. 2208, line 12: change ‘liner’ to ‘linear’

Answer: ok. Reviewer 1 also give this advice.

P. 2208, line 14: change ‘means’ to ‘suggests that’; the latter is more appropriate, given the limited dataset

Answer: This sentence has been deleted according to your above and Reviewer 1's advices.

P. 2208, line 15: change to ‘Figures 4a and 4b compare 32 mixed’

Answer: ok.

P. 2208, lines 16-17: consider changing to ‘from which it is evident that the mixed: : :’

Answer: ok. This part has been revised according to your above and Reviewer 1's advices.

P. 2208, line 18: change to ‘: : :to 2 mm, with minimal scatter and no apparent outliers.’

Answer: ok. This part has been revised according to your above and Reviewer 1's advices.

P. 2208, line 22: change to ‘gauge for mixed precipitation’

Answer: ok. This part has been revised according to your above and Reviewer 1's advices.

P. 2208, line 24: change to ‘a total of 26 field observations’

Answer: ok.

P. 2209, line 4: change to ‘close linear relationships are observed between’

Answer: ok.

P. 2209, line 5: change to ‘From Fig. 5c, there is a linear correlation between’

Answer: ok.

P. 2209, line 16: change ‘This means that’ to ‘This suggests that’

Answer: ok.

P. 2212, lines 2-3: change to ‘: : :and the ratios of Pit/CSPG for snowfall and mixed precipitation were 1.199 and 1.078, respectively’

Answer: ok.

Precipitation measurement intercomparison in the Qilian Mountains, Northeastern 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

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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 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$_{UN}$. Catch ratio (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-corrected method and precipitation accuracy in China. Results indicate that combined use of the CSPG$_{DFIR}$ and the CSPG$_{PIT}$ as reference

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

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).

Rodda (1967) early 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 (Sevruk and Hamon,1984). This gauge in a pit caught 6% more precipitation than the normally exposed gauge. In the second World Meteorological Organization (WMO) precipitation measurement intercomparison (Rain, 1972–1976), the pit with anti-splash grid was designated the reference standard shield for rain gauges (Goodison et al., 1998; Strangeways, 1998). In the third WMO precipitation measurement intercomparison (Snow, 1986–1993), the Double Fence International Reference (DFIR) shield with a Tretyakov shield was designated the reference standard snow gauges configuration (Goodison et al., 1989; Goodison et al., 1998; Sugiura et al., 2003). In the fourth WMO precipitation measurement intercomparison (Rain Intensity, 2004–2008), different principles were tested to measure rainfall intensity and define a standardized adjustment procedure (Lanza et al., 2005; Sevruk et al., 2009). 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; Yang, 2014) to define and validate automatic field instruments as references for gauge intercomparison, and to assess automatic systems and the operational networks for precipitation observations. The WMO-SPICE project still selected DFIR shield as part of the reference configurations.

The DFIR has been operated as part of reference configurations at 25 stations in 13 countries around the world (Golubev, 1985), but deviations from the DFIR measurements vary by gauge type and precipitation type (Goodison et al., 1998; Sevruk et al., 2009). 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. The wetting, evaporation losses and trace precipitation of CSPG were well quantified based on the huge observation data (Yang, 1988; Yang et al., 1991). 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 10m 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. Before the year 1993, 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 output new 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; 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 surrounding 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 surrounding 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 and single Alter shield (Struzer, 1971) around CSPGs ($CSPG_{UN}$ and $CSPG_{SA}$).

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) is used by the CMA to enhance catch ratios of automatic gauges (Yang, 2014), so the CSPG with SA shield ($CSPG_{SA}$) was selected as another intercomparison gauge. 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 $CSPG_{SA}$.

2 Data and Methods

2.1 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′, 2980m). 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 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=20cm, height=70cm), (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 cold season, the funnel and glass bottle are removed from the CSPG and precipitation is weighed under a windproof box to avoid wind effects. In the warm season, P is measured by volume. If there is frost on the collector, it will be wiped up by using a dry hand towel. In 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. For the CSPG, there are several methods of phase discrimination, 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 method 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 Methods

To asjust 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. The precipitation gauges in this work are CSPGs with the same P_g, P_w, P_e and P_t, thus P_{DFIR} can be used instead of KP_g in Eq.(1). For the CSPG, P_w is 0.23 mm for rainfall measurements, 0.30 mm for snow and 0.29 mm for mixed precipitation (Yang, 1988; Yang et al., 1991). The CSPG design reduces P_e to a value smaller than other losses in the warm, rainy season (Ye et al., 2004). In winter, P_e is already small (0.10–0.20mm/day) according to results in Finland (Aaltonen et al., 1993) and Mongolia (Zhang et al., 2004). A precipitation event of less than 0.10 mm is beyond the resolution of the 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.

The most important factor influencing precipitation measurement in high mountain conditions is wind, which is the focus of the present study. The WMO has given Eqs.(2)-(4) for the shielded Tretyakov gauge catch ratio (CR=1/K*100=P_g/P_{DFIR}*100, %) 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).

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

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) and Ye et al. (2007) 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).

This field experiment focusses 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 $CSPG_{UN}$ and $CSPG_{SA}$ by using $CSPG_{DFIR}$ as reference. Total 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 speed at the gauge height ($W_{s0.7}$) and 10 m height (W_{s10}) was calculated by using half-hourly wind speed data at 1.5 m and 2.5 m heights, according to the Monin-Obukhov theory and the gradient method (Bagnold,1941; Dyer and Bradley, 1982):

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

$$W_{sz} = k_z W_{s1.5}, \quad k_z = \frac{\ln(z/z_0)}{\ln(1.5/z_0)} \qquad (9)$$

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 relationships 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 $CSPG_{SA}$ 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 $CSPG_{DFIR}$ caught more 3.6% and 2.5% rainfall than $CSPG_{SA}$, 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 $CSPG_{DFIR}$ or the other gauges (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 $CSPG_{SA}$, 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 $CSPG_{UN}$, respectively. The $CSPG_{PIT}$ and $CSPG_{DFIR}$ caught more 7.3% and 6.0% mixed *P* than $CSPG_{SA}$, respectively. Whereas the $CSPG_{DFIR}$ caught 1.2% less mixed *P* than the $CSPG_{PIT}$ (Table 3).

Close linear relationships are observed among the gauges (Fig.3). The $CSPG_{PIT}$ caught 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 $CSPG_{SA}$ 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 $CSPG_{UN}$, respectively. The $CSPG_{PIT}$ and $CSPG_{DFIR}$ caught more 4.4% and 8.5% snowfall than $CSPG_{SA}$, respectively (Table 3).

Close linear relationships are observed between the $CSPG_{DFIR}$ and each of the other three gauges (Fig.4). From the 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 total difference of 43-time snowfall between the $CSPG_{DFIR}$ and the $CSPG_{PIT}$ was only about 3.4 mm. 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 $CSPG_{SA}$ 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 CSPG, it is 0.7m.) and air temperature data.

To minimize ratio scatter of among different gauges, precipitation events greater than 3mm 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 3mm. For this reason, single or daily snowfall and mixed precipitation greater than 1mm was used here. Whereas for the rainfall, precipitation greater than 3mm was selected. The catch ratio vs. wind speed relations of different precipitation types are summarized in Table 4. 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 $CR_{UN/DFIR}$ or $CR_{SA/DFIR}$ 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).

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

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

Where $CR_{UN/DFIR,Rain}$ and $CR_{SA/DFIR,Rain}$ is the rainfall catch ratio (%) of $CSPG_{UN}$ and $CSPG_{SA}$, 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 $\alpha=0.25$ (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 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 and with an α value of about 0.16 (Table 4).

Fig.6 about here

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

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

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 an α value of about 0.12 (Table 4).

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

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

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 $CR_{SA/DFIR,Snow}$ vs. W_{s10} relations are evident (Table 4, Fig.7). For the $CSPG_{UN}$, the exponential relationship Eq. (18) passes the F-test when α<0.001. For the $CSPG_{SA}$, the power law expression Eq.(19) passes the F-test when α<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 α<0.001 and α<0.10, respectively (Table 4). Eqs. (18) - (21) could be directly used to calibrate the wind-induced snowfall measurement errors for $CSPG_{UN}$ and $CSPG_{SA}$.

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

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

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.

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

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

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 and 1.072, and the ratios of $CSPG_{PIT}/CSPG_{UN}$ for snowfall and mixed precipitation were 1.162 and 1.082, respectively (Fig.3 and Fig.4). 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 and Li (2007) 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 often appeared at the western mountainous stations. 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 similar with Ren and Li (2007) presented.

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 snowfall, the catch ratio for the $CSPG_{PIT}$ is 0.96, close to the $CSPG_{DFIR}$ catch ratio. The total 43-time snowfall difference of $CSPG_{PIT}$ and $CSPG_{DFIR}$ 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. 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

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 $CSPG_{UN}$ 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
P (mm)	3.5	2.5	11.0	8.8	67.7	69.6	87.1	111.6	57.7	24.0	2.7	1.0	447.2
T_{mean} (^oC)	-4.1	-2.6	-1.5	0.7	2.3	3.7	4.2	4.0	2.7	0.5	-1.9	-3.8	0.4
T_{max} (^oC)	-1.3	0.2	1.2	3.4	4.8	6.1	6.5	6.6	5.1	3.4	1.2	-0.6	3.0
T_{min} (^oC)	-6.3	-4.9	-3.9	-1.7	0.2	1.6	2.3	1.9	0.6	-1.8	-4.2	-6.1	-1.9
$W_{s1.5}$ (m s^{-1})	0.60	0.65	0.77	0.85	0.81	0.66	0.61	0.60	0.64	0.60	0.69	0.65	0.68
$W_{s2.5}$ (m s^{-1})	0.60	0.67	0.81	0.92	0.88	0.72	0.68	0.67	0.72	0.66	0.73	0.67	0.73
E_0 (mm)	31.6	47.0	79.4	124.4	140.9	155.0	141.7	127.0	101.6	75.2	47.3	31.0	1102.2

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

Gauge	Abbreviation	Size(φ stand for orifice diameter and h for observation height)	Start date	End date	Measure time
An unshielded China standard precipitation gauge	$CSPG_{UN}$	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	*P* type	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 type	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 type	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 vs. wind speed relations at the Hulu watershed intercomparison site, 2012-2015.

Temporal scale	*P* type	Gauges	Best catch ratio vs. wind speed relation*	*P* (mm)	No. of events	F-test
Single *P*	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 *P*	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).

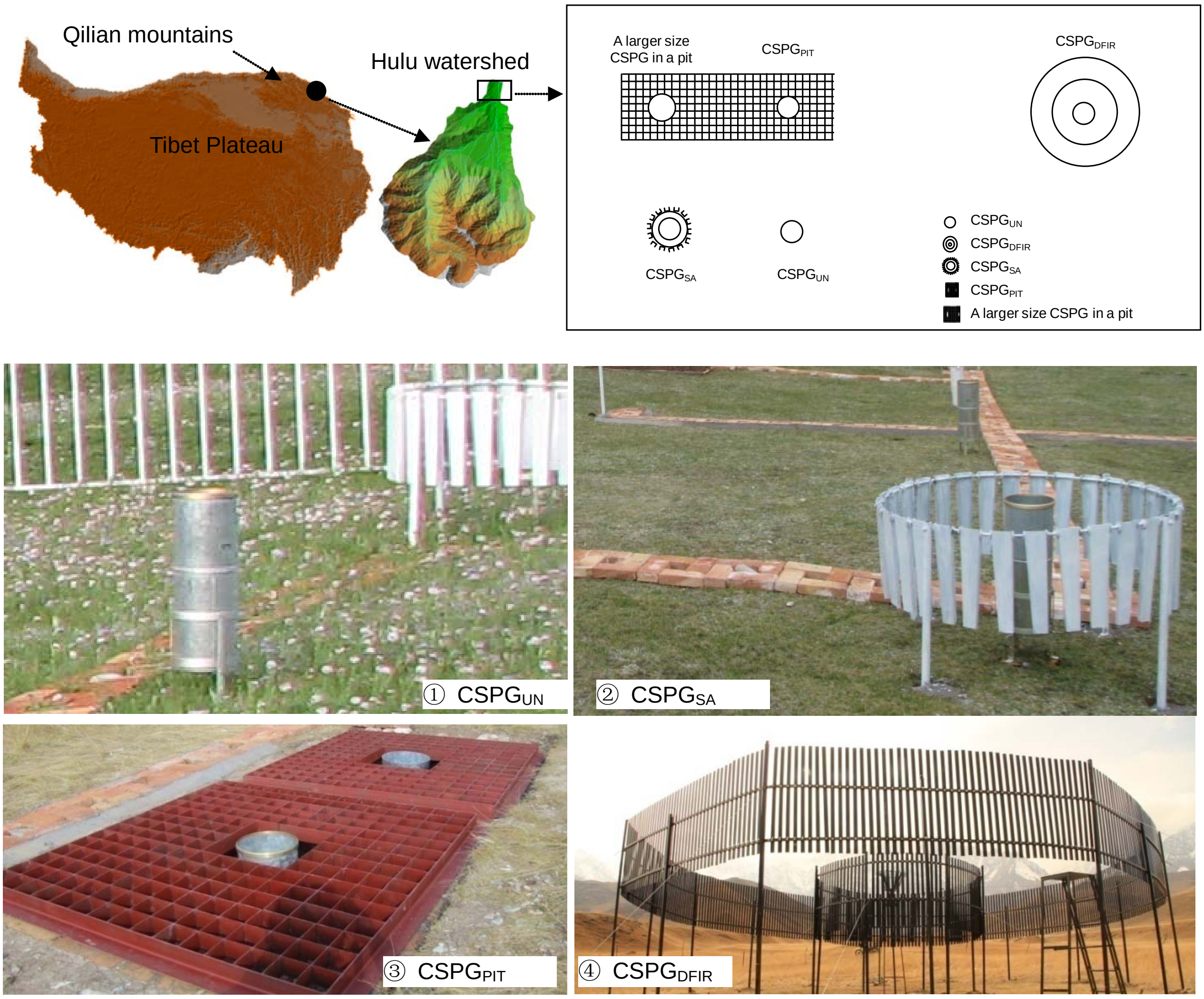

Figure 1. Precipitation gauge intercomparison experiment in the Qilian mountains, Tibetan Plateau.

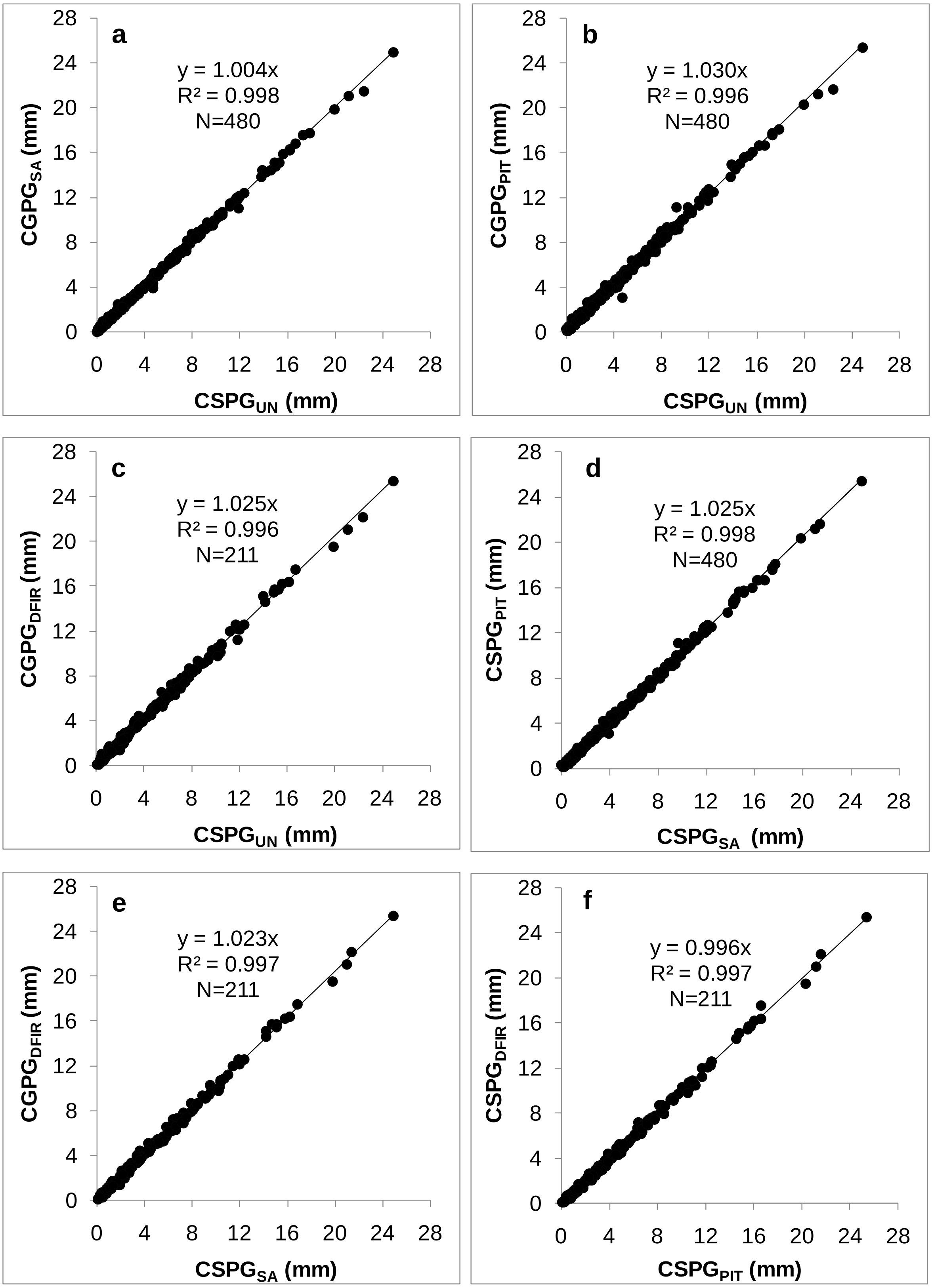

Figure 2. Scatter plots for rainfall of CSPG$_{UN}$, CSPG$_{SA}$, CSPG$_{PIT}$ and CSPG$_{DFIR}$ from September 2010 (**a**, **b** and **d**) or September 2012 (**c**, **e** and **f**) to April 2015**.**

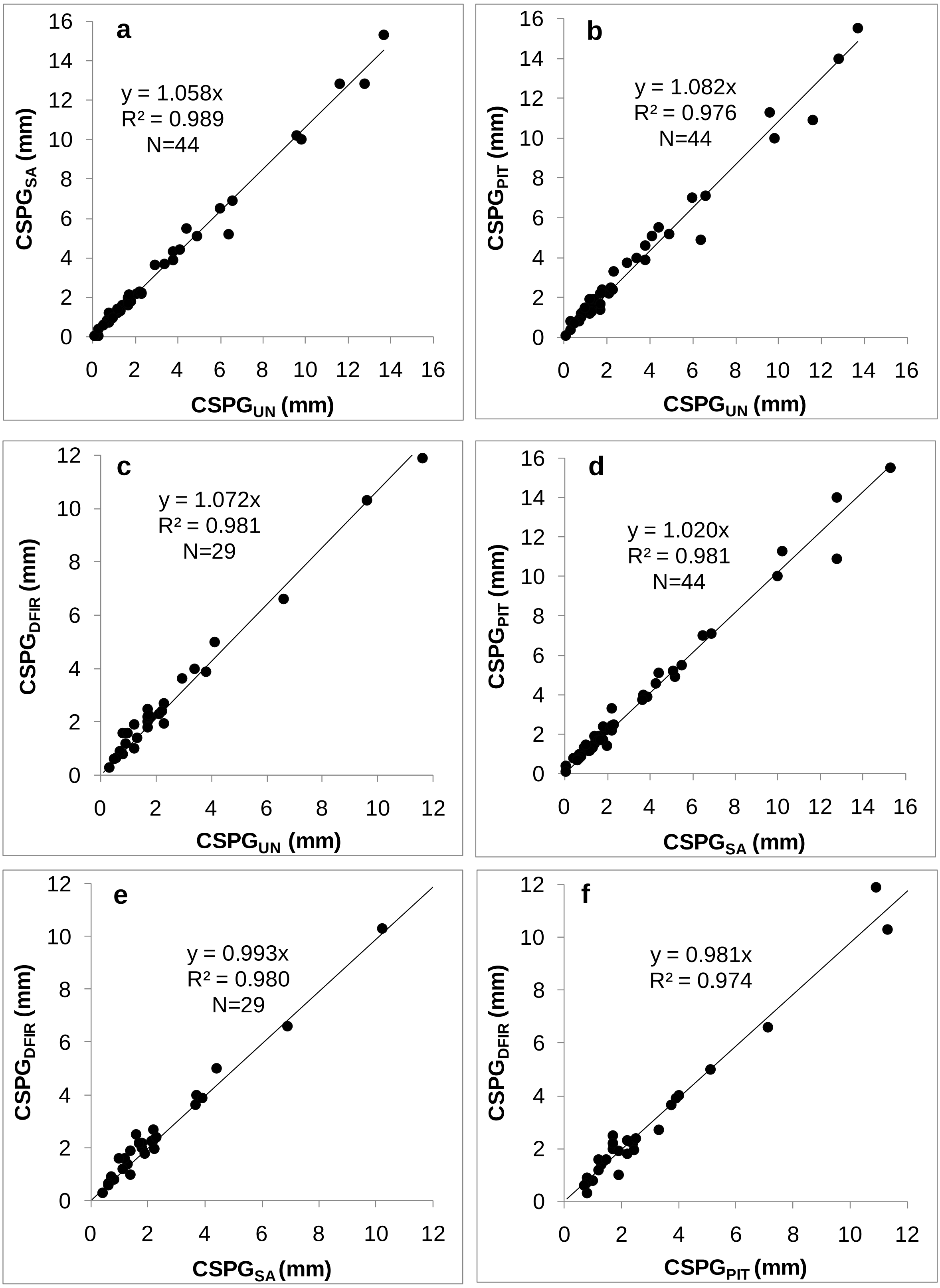

Figure 3. Scatter plots for mixed precipitation of $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ from September 2010 (**a**, **b** and **d**) or September 2012 (**c**, **e** and **f**) to April 2015**.**

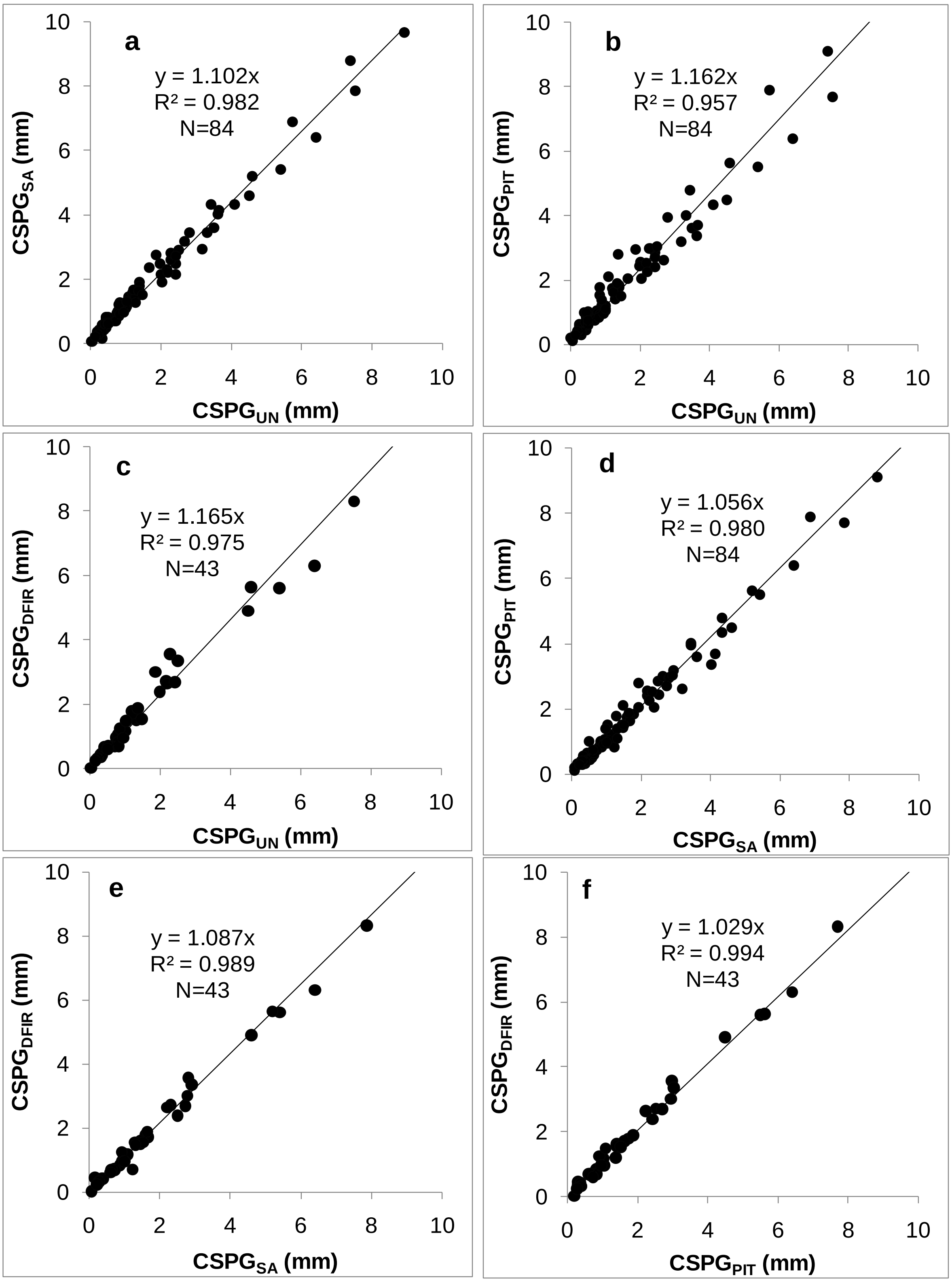

Figure 4. Scatter plots for snowfall of $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ from September 2010 (**a**, **b** and **d**) or September 2012 (**c**, **e** and **f**) to April 2015**.**

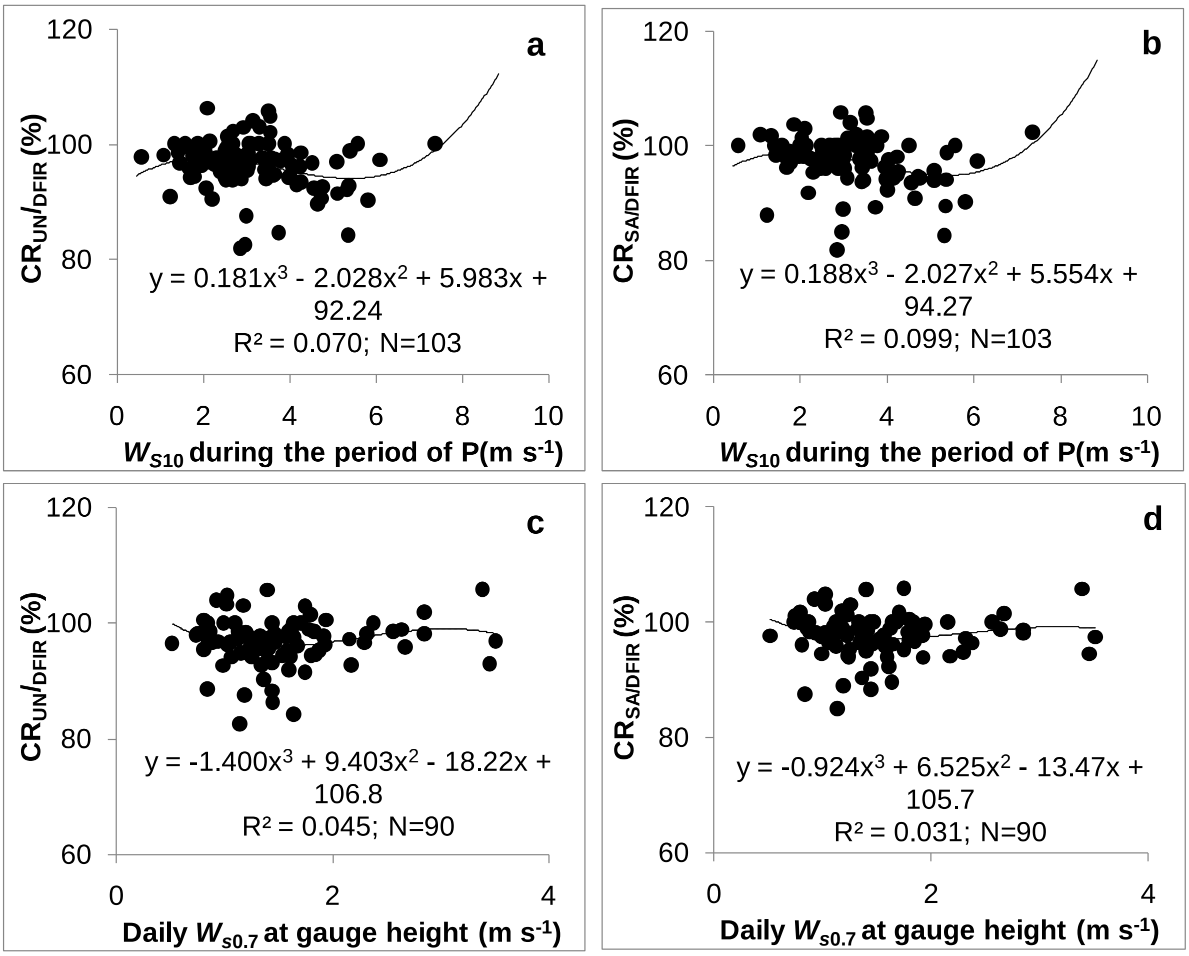

Figure 5. Rainfall CRs vs. wind speed for rainfall event (**a** and **b**) and daily rainfall (**c** and **d**) greater than 3.0mm.

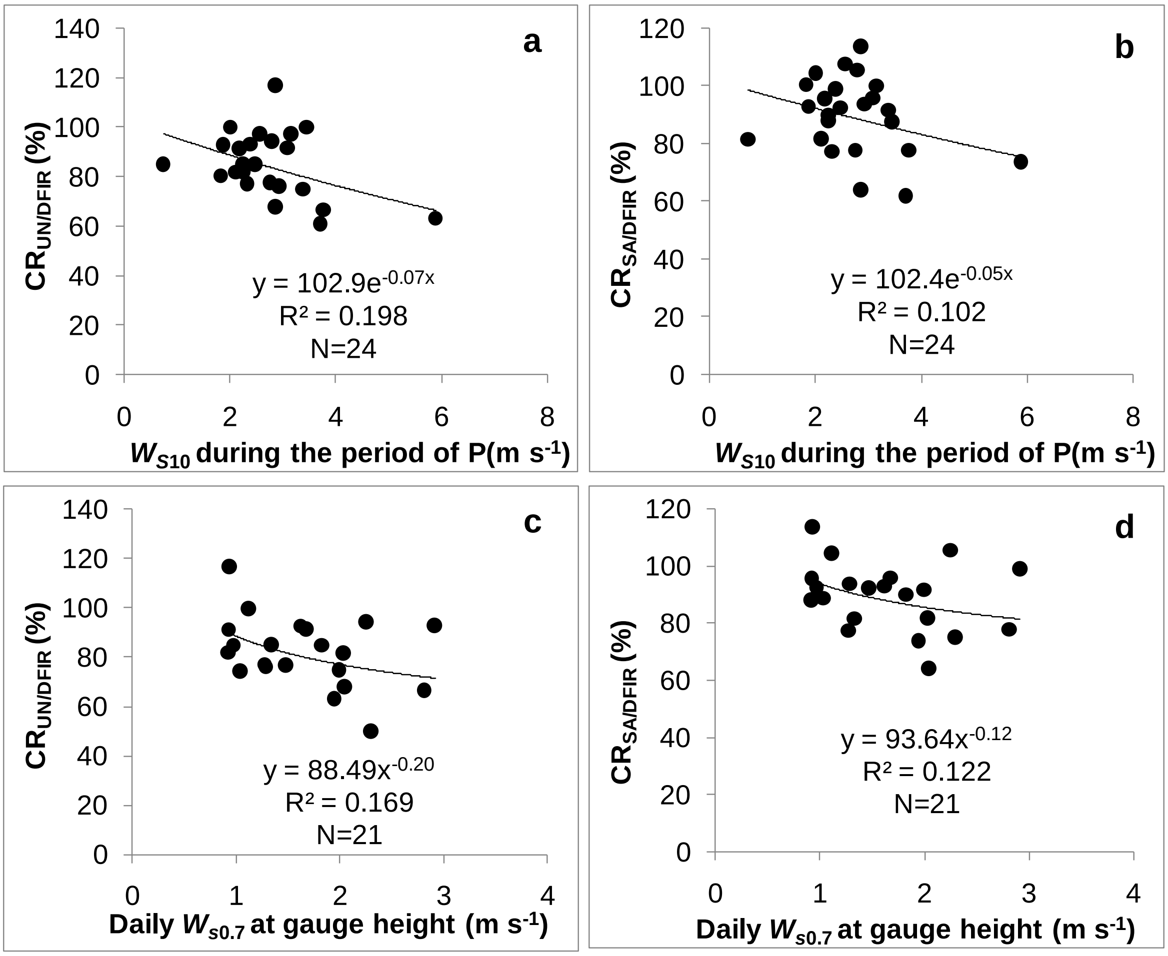

Figure 6. CRs vs. wind speed for mixed precipitation event (**a** and **b**) and dailymixed precipitation (**c** and **d**) greater than 1.0mm.

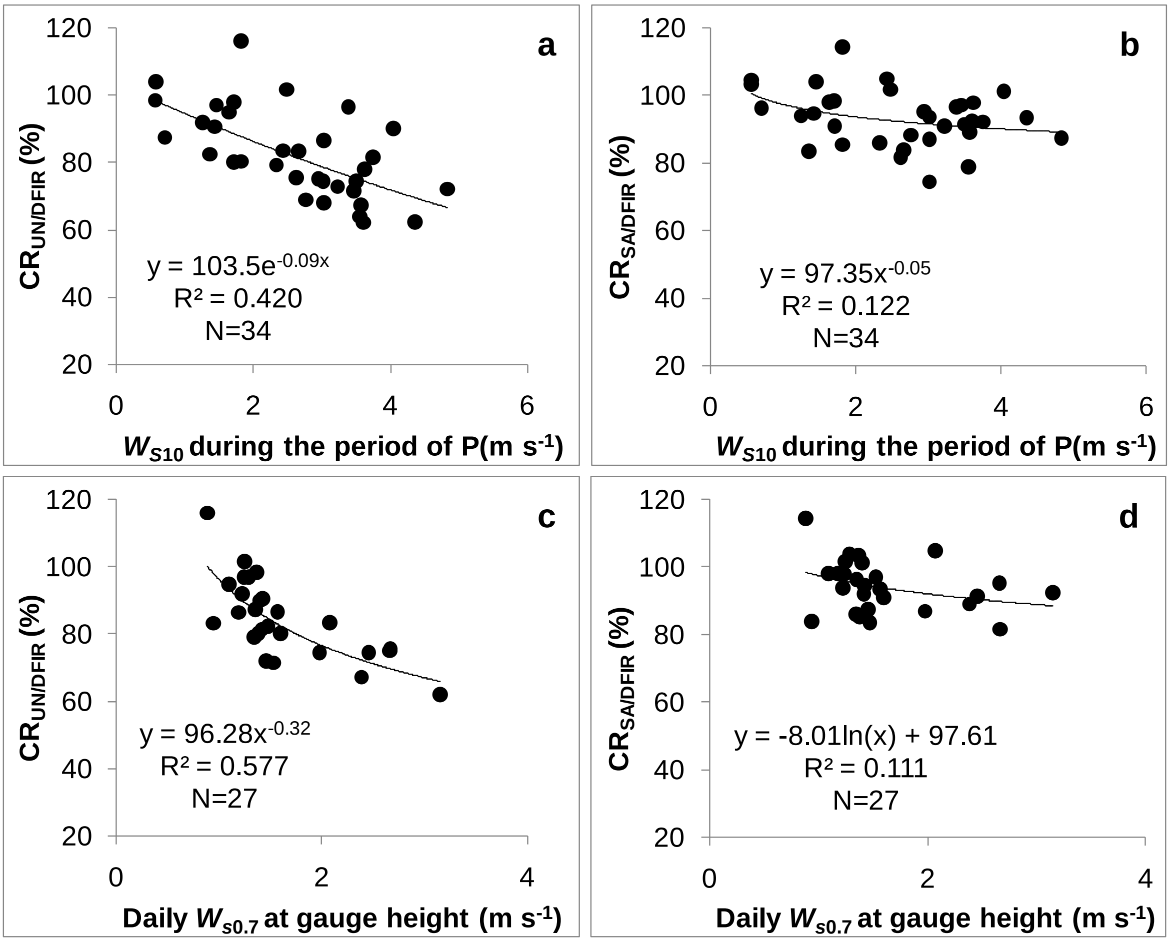

Figure 7. CRs vs. wind speed for snowfall event (**a** and **b**) and daily (**c** and **d**) snowfall greater than 1.0mm.

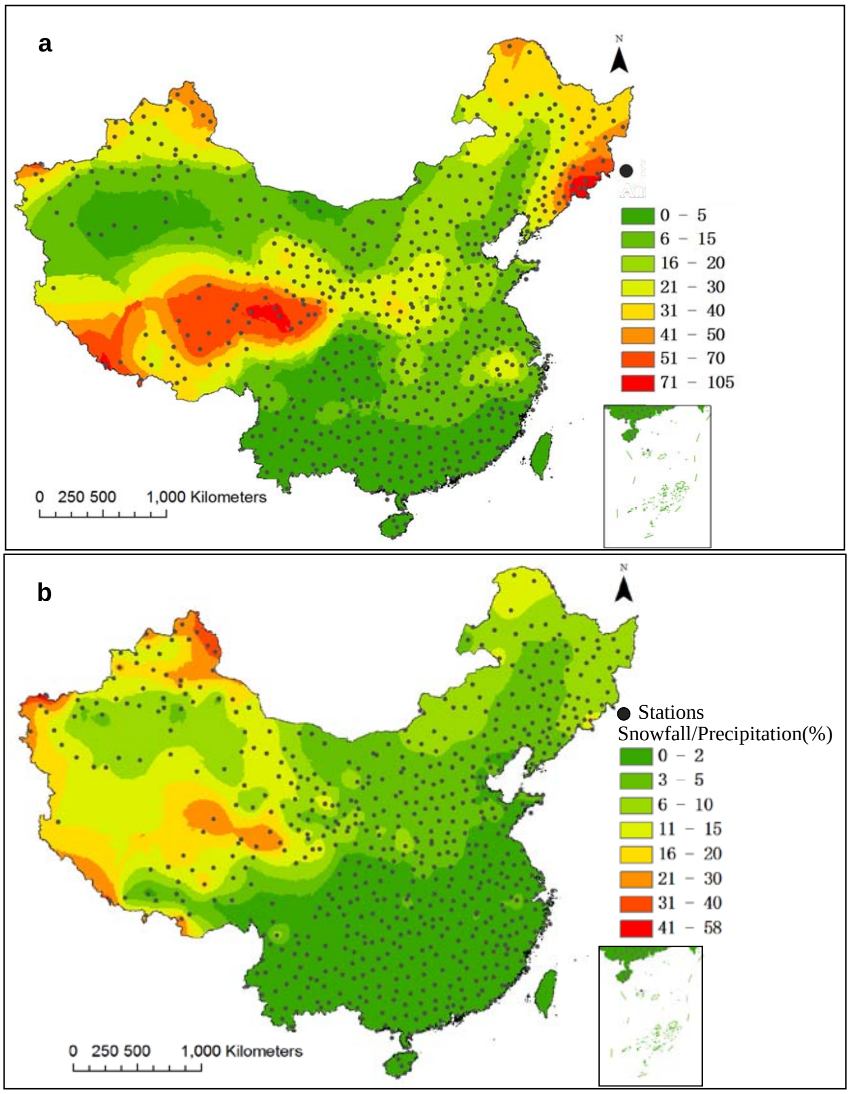

Figure 8. (**a**) Annual snowfall (mm) and (**b**) snowfall proportion (annual snowfall/annual precipitation) in China.

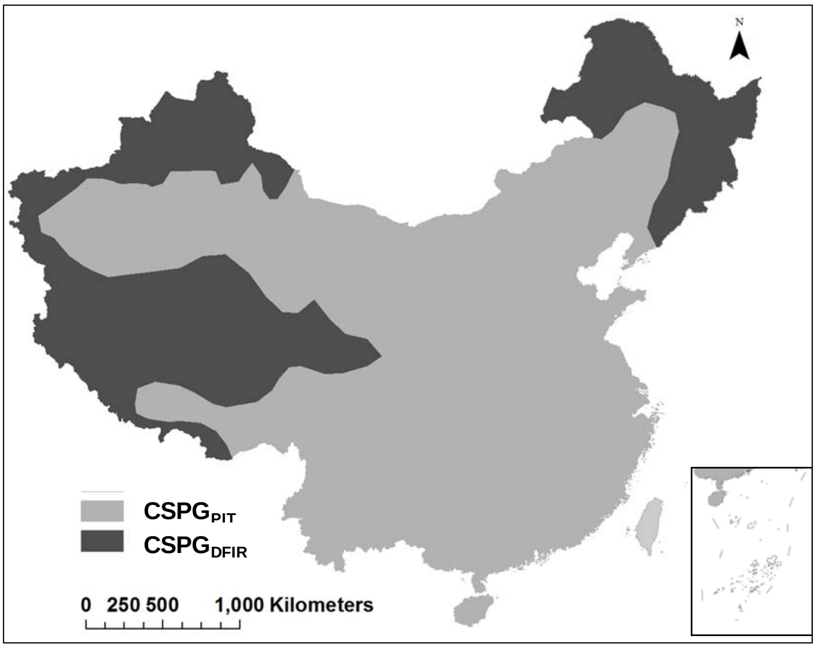

Figure 9. Applicable regions for the CSPG$_{PIT}$ and the CSPG$_{DFIR}$ as reference gauges in China.