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

Anonymous Referee #1

Received and published: 21 April 2015

Comments from Referees:

GENERAL COMMENTS (I also produced a JPG version of this comments due to the lost of subscripts I used in my review)

The focus of the paper is the quality assessment of manual precipitation observations made with CSPG gauge, which is the standard manual gauge in China. It is placed into four different environments: put into a PIT reference, applied DFIR and Single Alter (SA) shield and in an environment without any shields. After describing the data and methodologies, the connection between the four installations are presented using scattered graphs and ratio vs wind speed graphs. Based on the results the authors suggest areas for the applicability of reference installment (PIT vs DFIR).

This publication deals with only one precipitation gauge (CSPG), so the applicability of the results is limited. The analysis is based on 4 years of observation record, which is the bare minimum for similar analysis. The applied ratio vs wind speed fitting equations are always linear in the paper. While this may be satisfactory, the WMO recommendation should also be mentioned and possibly tried out.

The wind speed was converted to the 10 m value, the WMO recommendation is to use the wind speed value at the gauge heights – this should be corrected or the reason behind it should be explained further. Some of the results will be affected by this suggested change.

Author's response: Thank you very much for your good advices.

Author's changes in manuscript:

1) The used data are updated to April 30 2015. During October 2014 to April 30 2015, there occurs 29 mixed (snow with rain) and snowfall events which would improve the results.

2) All the relevant figures, tables and equations are changed because of the new added data.

3) The INTRODUCTION part has been rewritten. The sentences are reworded, some new sentences and new reference in the literature are added. After revision, the clearness, logic, and completeness etc. are much improved in the INTRODUCTION part.

4) The Chapter 'DATA AND METHOD', RESULTS, etc. are all rewritten.

5) Total two kinds of catch ratio (CR) vs. wind speed equations are tried for snow, rain and mixed precipitation. One is designed for easy application in China by using the precipitation event data and wind speed at 10m height which is observed at all the stations of China Meteorological Administration (CMA). Another uses daily precipitation, wind speed at gauge height and air temperatures similar to the WMO recommendation. This part will be shown in the relevant SPECIFIC COMMENTS part.

6) The best CR vs. wind speed relationship are found by using the longer period data. The CR is calculated by

using the $CSPG_{DFIR}$ as the only reference. These equations are tested by using F-test method. These equations are summarized in the Table 4, and some important equations are shown as equations and in the figures. The Table 4 is shown below:

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

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

	Snow	$CSPG_{UN}$	$CR_{UN/DFIR,Snow} = 96.28W_{s0.7}^{-0.32}$ R^2=0.577	P>1.0	27	α=5.7E-6
		$CSPG_{SA}$	$CR_{SA/DFIR,Snow} = -8.01\ln(W_{s0.7}) + 97.61$ R^2=0.111			α=0.09
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Snow} = -5.760W_{s0.7}^3 + 41.641W_{s0.7}^2 - 93.05W_{s0.7} + 160.5$ R^2=0.134			α=0.33

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

Comments from Referees:

It is hard to read the paper, since the terminology used is often confusing. The words “Alter”, “Pit” and “DFIR” are often refer to gauges, when the authors meant the shield/gauge configuration with the CSPG gauge in the middle. The authors reference the SPICE experiment. I suggest using the shield notations used in the related literature: UN for UNshielded gauge, SA: for Single Alter shield, PIT and DFIR (no change required). So the four types of precipitation observations made with the CSPG gauge would be: (1) CSPGPIT , (2) CSPGDFIR , (3) CSPGSA , (4) CSPGUN.

Author's response: Thank you very much for your good advices.

Author's changes in manuscript:

All the relevant terminology in the text, tables and figures has be revised in the revised paper. For example, in the Chapter 2.1 INTERCOMPARISON EXPERIMENTS AND RELEVANT DATA, relevant part is described as: " The intercomparison experiments included (1) an unshielded CSPG ($CSPG_{UN}$; orifice diameter=20 cm, height=70 cm), (2) single Alter shield around a CSPG ($CSPG_{SA}$), (3) a CSPG in a pit ($CSPG_{PIT}$), and (4) a DFIR shield with a Tretyakov-shielded CSPG ($CSPG_{DFIR}$) (Fig.1, Table 2).' Table 2 is revises as:

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

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

Comments from Referees:

The abstract contain the comparative results of (1)-(2), (1)-(4) and (2)-(4). For completeness, the results for the missing (1)-(3), (2)-(3) and (3)-(4) relations should also be mentioned.

Author's response: Thank you very much for your good advices.

Author's changes in manuscript: These results have been described both in the ABSTRACT and in the relevant text. For example, in the ASBSTRACT, the relevant part has been revised as:

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.

Comments from Referees:

Also, the word “shelter” should be replaced at each occurrence with the alternate and term “shield”, which is widely used in the literature.

Author's response: Thank you very much for your good advices.

Author's changes in manuscript: All the 'shelter' has been replaced by 'shield'. A total of 27 parts in the manuscript have been changed.

Comments from Referees:

SPECIFIC COMMENTS:

P2203/L9: Correct 30.5 m to 30.5 cm

Author's response: ok.

Author's changes in manuscript: It has been corrected.

Comments from Referees:

P2203/L25: Please correct: the WMO SPICE reference is DFIR shield.

Author's response: ok. It has been corrected.

Author's changes in manuscript: It has been corrected as " The WMO-SPICE project still selected DFIR shield as part of the reference configurations."

Comments from Referees:

P2204/L4: Add more recent reference

Author's response: ok.

Author's changes in manuscript: It has been changed as "The DFIR has been operated as part of reference configurations at 25 stations in 13 countries around the world (Golubev, 1985; Sevruk et al., 2009)", ...

Comments from Referees:

P2204/L5: Please reword: the CSPG and Hellmann gauges placed into a DFIR shield was compared (if I understand correctly). DFIR is not a gauge, it is a shield.

Author's response: ok.

Author's changes in manuscript: This sentence has been changed as " In China, the Chinese standard precipitation gauge (CSPG) and the Hellmann gauge were firstly compared by using DFIR shield as reference configurations in the valley site of Tianshan (43°7′ N, 86°49′ E, 3720 m), during the third WMO precipitation measurement intercomparison experiment from 1987 to 1992 (Yang, 1988; Yang et al., 1991)."

Comments from Referees:

P2204/L11: Please add distance between the two sites

Author's response: ok.

Author's changes in manuscript: This sentence has been changed as " The wetting, evaporation losses and trace precipitation of CSPG were well quantified based on the huge observation data. Because there are not wind data at the intercomparison site (Yang et al., 1991; Goodison et al., 1998), for the wind-induced undercatch, the derived CSPG catch ratio equations were based on the 10 m height wind speed at the open Daxigou Meteorological Station (43.06°, 86.5°E, 3540 m; Yang, 1988; Yang et al., 1991). The distance is about 1.7 km between the Daxigou site and the Tianshan valley site thus their wind speeds are different, inducing uncertainty in the catch ratio equations established by Yang et al. (1991) for the CSPG."

Comments from Referees:

P2204/L23: Instead of Alter shield (ALTER) please use the generally used term (reference: SPICE) of Single Alter (SA) shield here and in the future

Author's response: ok.

Author's changes in manuscript: The four installments are used the terminology as '$CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$'.

Comments from Referees:

P2204/L27: First appearance of mixed precipitation – please define it.

Author's response: ok.

Author's changes in manuscript: It has been defined as "snow with rain; rain with snow" in the abstract and fist appearance in the text.

Comments from Referees:
P2205/L10: The value of 447 mm is quite precise – I suggest rewording the sentence like: Annual average precipitation is 447 mm for the test period of: : :

Author's response: ok.

Author's changes in manuscript: It has been changed as " Annual precipitation is about 447.2 mm during 2010-2012 and precipitation mostly occurs during the warm season from May to September at this site."

Comments from Referees:
P2205/L17: Delete etc.

Author's response: ok.

Author's changes in manuscript: It has been deleted.

Comments from Referees:
P2205/L18: I suggest replacing "shown" with "summarized".

Author's response: ok.

Author's changes in manuscript: The specific meteorological conditions at the site are summarized in Table 1.

Comments from Referees:
P2205/L22: Not clear, what type of gauge is in the middle of the DFIR shield: CSPG or Tretyakov gauge? Please specify. I assume it is also a CSPG gauge with a wind shield described in the Goodison et al. (1998) WMO reference guide.

Author's response: Yes, it is not clear.

Author's changes in manuscript: It has been revised as:" and (4) a DFIR shield with a Tretyakov-shielded CSPG ($CSPG_{DFIR}$) ".

Comments from Referees:
P2207/L11: The terminology is mixed up here. CSPG is the gauge, placed into different environment. I suggest to use the terminology I explained earlier for these two cases: CSPGPIT , CSPGSA

Author's response: Ok.

Author's changes in manuscript: The four installments are used the terminology as '$CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$' in the whole manuscript.

Comments from Referees:
P2207/L17 and 20: These are not the actual observations taken. I assume the "observations" meant "precipitation events" here.

Author's response: Yes, they are precipitation events.

Author's changes in manuscript: this part has been revised as: "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."

Comments from Referees:
P2207/L21: Again, the "Alter, Pit and DFIR" are not gauges but shield. Suggest to use CSPGUN (no shield around the gauge = Unshielded), CSPGSA , CSPGPIT CSPGDFIR in the text and also in the tables.

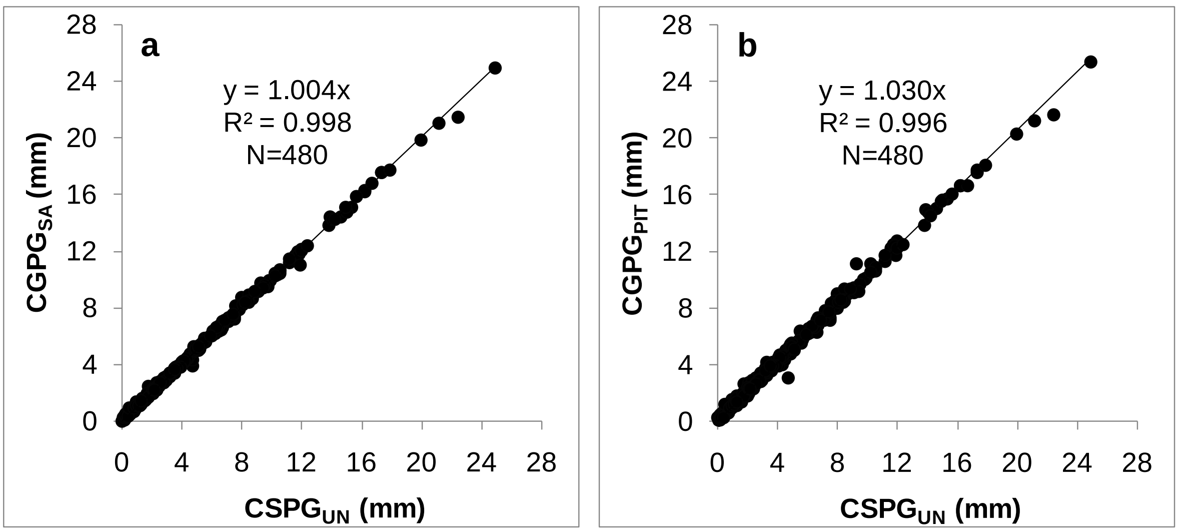
Author's response: ok.

Author's changes in manuscript: The four installments are used the terminology as '$CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$' in the whole manuscript.

Comments from Referees:
P2207/L24: There are no "three different gauges" but one gauge with different shields / different installments.

Author's response: ok.

Author's changes in manuscript: It has been changed as " Good linear correlations are found among the four CSPG installments (Fig.2).". Fig.2 are redrawn as your above advices. The intercomparson among the four installments are shown in the new Fig.2.



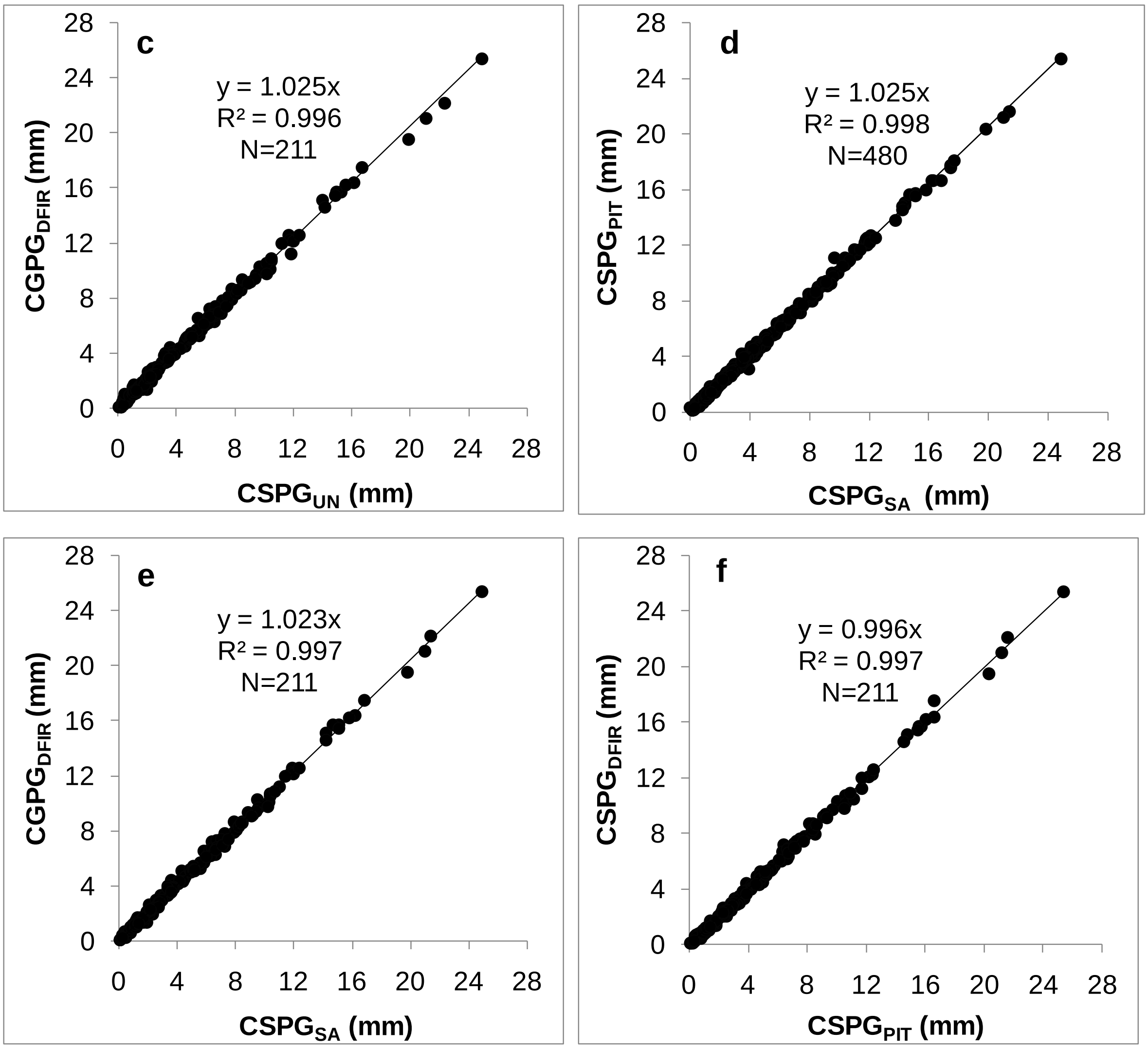


Figure 2. Intercomparison plots among $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ for the rainfall events from September 2010 (**a**, **b** and **d**) or September 2012 (**c**, **e** and **f**) to April 2015**.**

Comments from Referees:

Chapters 3.1, 3.2 and 3.3 and Figures 2-6: Same comment then before: the Alter, Pit and DFIR are not gauges but shields. I suggest to use CSPGUN (no shield around the CSPG gauge = Unshielded), CSPGSA (Single Alter SA shield around the CSPG gauge), CSPGPIT (CSPG gauge in a PIT) and CSPGDFIR (DFIR shield around the CSPG gauge) in the text and also in the tables.

Author's response: ok.

Author's changes in manuscript: The four installments are used the terminology as '$CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$' in the whole manuscript.

Comments from Referees:

Table 3 should also include all the percent values (ratios) mentioned in the text. It would be easier to follow then.

Author's response: ok.

Author's changes in manuscript: Table 3 has been revises as:

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

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

Comments from Referees:

Chapter 3.1 (rain): Please include the comparison of unshielded and single alter shield gauge performance $CSPG_{UN}$ and $CSPG_{SA}$

Author's response: ok.

Author's changes in manuscript: This paragraph has been changed :

Good linear correlations are found among the four CSPG installments (Fig.2). From September 2010 to April 2015, the $CSPG_{PIT}$ caught 4.7% and 3.4% more rainfall than the $CSPG_{UN}$ and $CSPG_{SA}$ 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).

Comments from Referees:

Chapter 3.2 (mixed): Again, there is only one type of gauge in different setup. Also, the longer 2010-2014 period ratios (Pit vs other) are missing from this chapter.

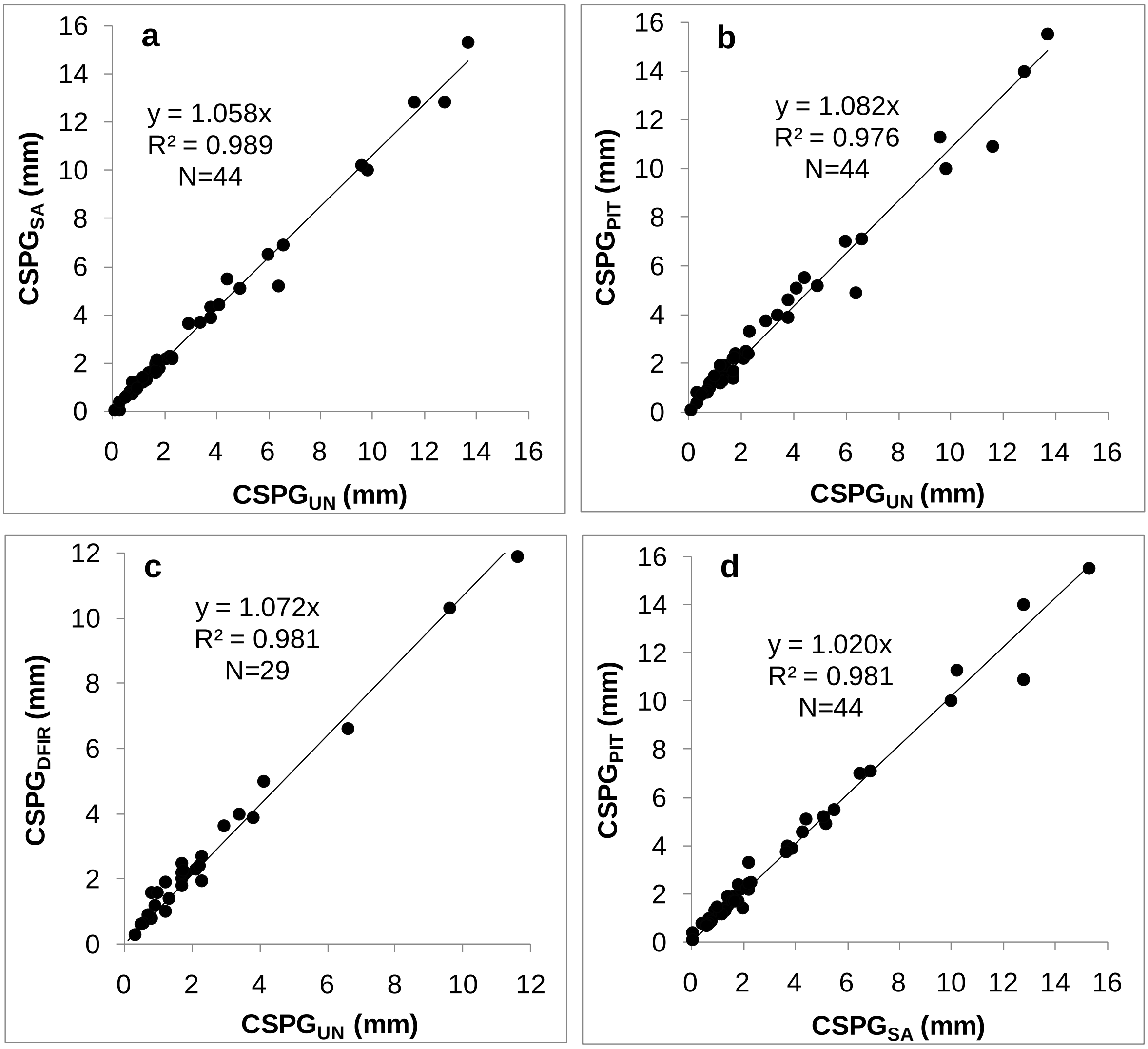
Author's response: ok.

Author's changes in manuscript: These paragraphs have been changed :

From September 2010 to April 2015, a total of 44 mixed precipitation events were observed. The $CSPG_{PIT}$

caught 12.1% and 5.6% more mixed P than the $CSPG_{UN}$ and the $CSPG_{SA}$, respectively. The $CSPG_{SA}$ caught 6.1% more mixed P than the $CSPG_{UN}$ (Table 3). From September 2012 to April 2015, the $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DIFR}$ caught 7.7%, 15.6% and 14.2% more mixed P than the $CSPG_{UN}$, respectively. The $CSPG_{PIT}$ and the $CSPG_{DFIR}$ caught more 7.3% and 6.0% mixed P than the $CSPG_{SA}$, respectively. Whereas the $CSPG_{DFIR}$ caught 1.2% less mixed P than the $CSPG_{PIT}$ (Table 3).

Good linear correlations are observed among the gauges (Fig.3). The $CSPG_{PIT}$ caught 1.1mm 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.



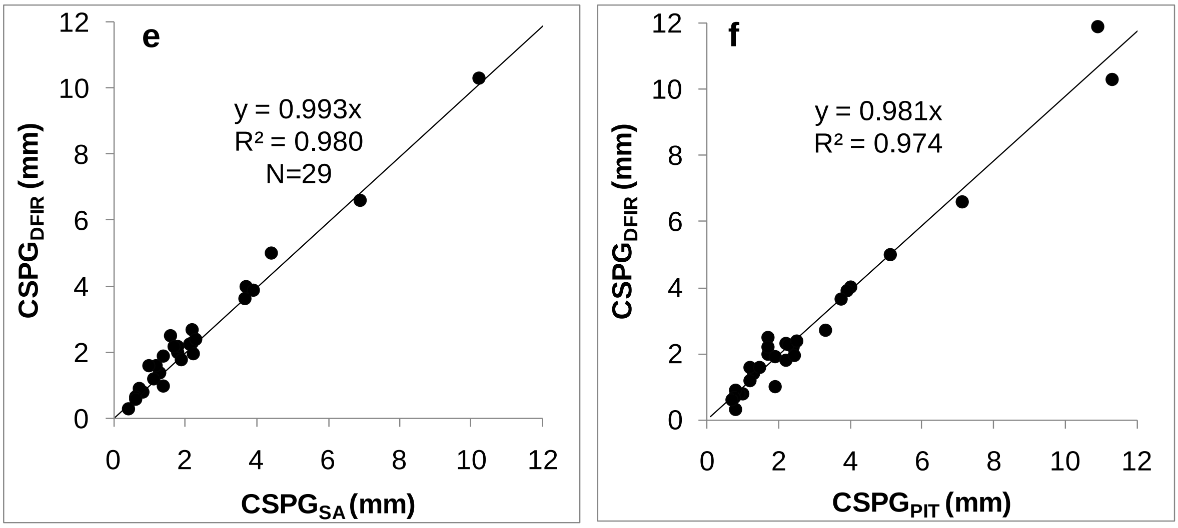


Figure 3. Intercomparison plots among $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ for the mixed precipitation events from September 2010 (**a**, **b** and **d**) or September 2012 (**c**, **e** and **f**) to April 2015**.**

Comments from Referees:

P2208/L12: replace "liner" with "linear"

Author's response: ok.

Author's changes in manuscript: It has been replaced.

Comments from Referees:

Chapter 3.3 (snow): Missing CSPGPIT and CSPGDFIR comparison. Here the analysis for all events is added. To be consistent, please add all event results to the rain and snow chapters as well.

Author's response: ok.

Author's changes in manuscript: These paragraphs have been changed :

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

Good linear correlations are also observed between the $CSPG_{DFIR}$ and each of the other three gauges (Fig.4). From 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 difference of total snowfall (43 events) between the $CSPG_{DFIR}$ and the $CSPG_{PIT}$ was only about 3.4 mm (Table 3). This suggests that the $CSPG_{PIT}$ could be used as the reference gauge for snow precipitation events at the experiment site.

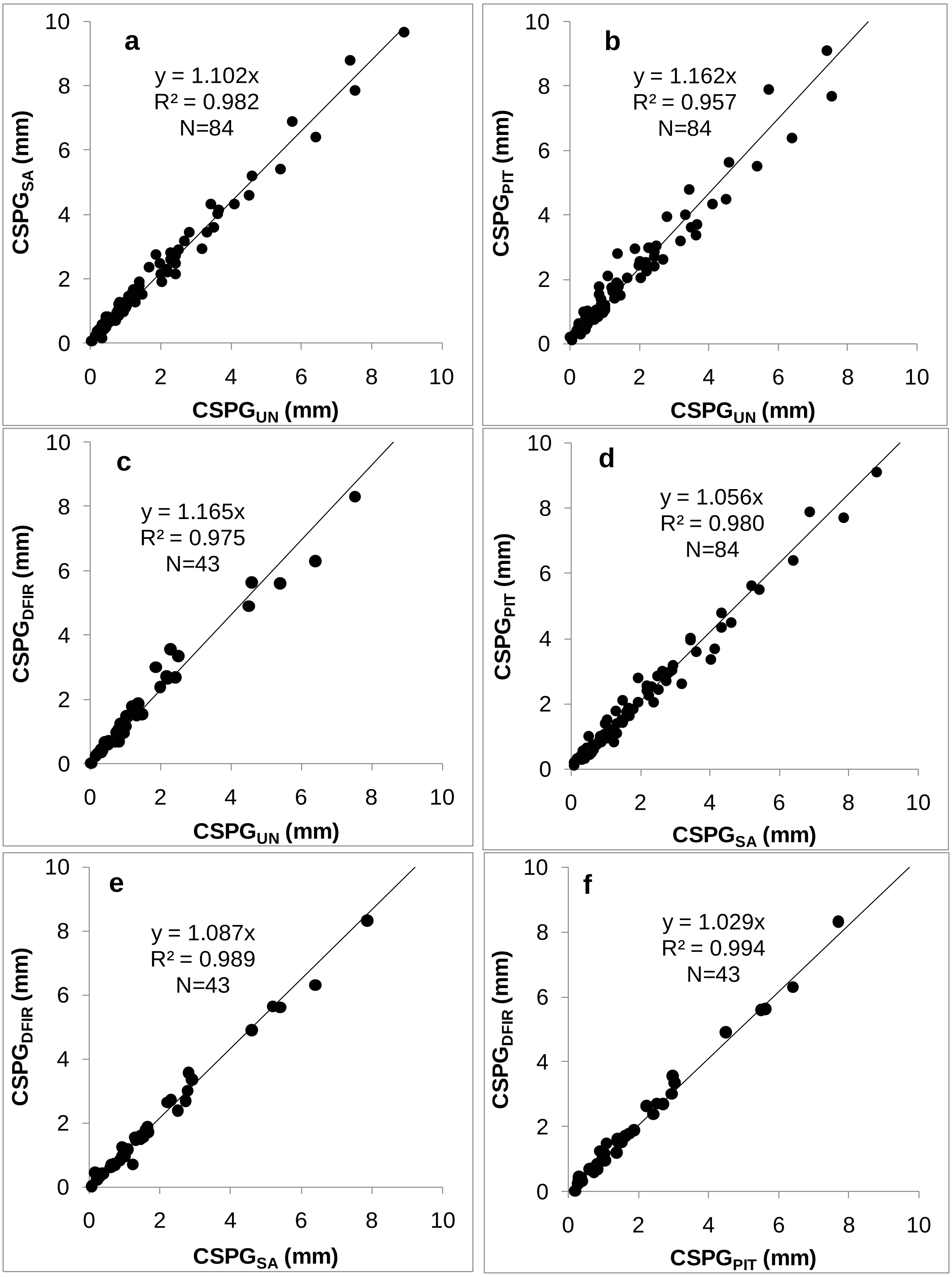


Figure 4. Intercomparison plots among $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ for the snowfall events from September 2010 (**a**, **b** and **d**) or September 2012 (**c**, **e** and **f**) to April 2015**.**

Comments from Referees:

Chapter 3.4: Why do we need the 10 m wind speed? From Goodison et al, 1998: “To adjust gauge measurements for any wind induced bias, wind speed at gauge height during the time of precipitation is required.”

Author's response: Because the wind speed is measured at 10m heights at all the CMA stations in China, here the 10m wind speed data are used. As described above, the wind speed data at gauge height has also been used in the equations liking the WMO recommendation equations (Eqs.2-4) for daily precipitation.

Author's changes in manuscript:

In the Chapter "2.2 ADJUSTMENT METHOD" in the revised paper, it is revised as:

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

In the Chapter 3.4, it is revised as:

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.

Comments from Referees:

Chapter 3.41: The assumption used here is that the gauge ratios for rain vs wind relation is linear. In the Goodison et al (1998) WMO reference the suggested form is 3rd order relationship with wind.

Author's response: This equation has been revised by using new data updated to April 30 2015.

Author's changes in manuscript: The new equations are shown in Table 4, Fig.5 and in Eqs. (10) and (11).

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

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

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}).

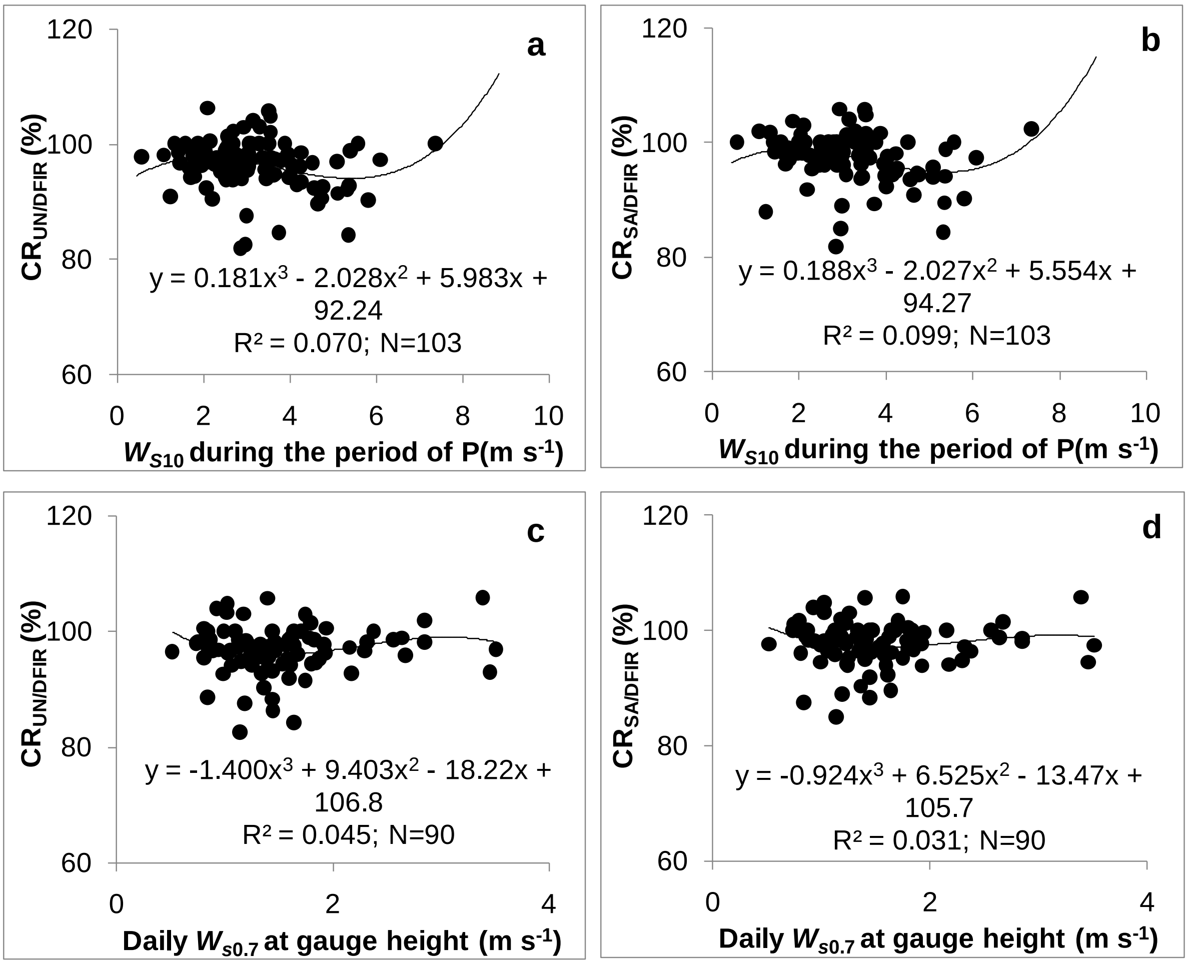


Figure 5. Catch ratios (CRs) vs. wind speed for the rainfall event (**a** and **b**) and the daily rainfall (**c** and **d**) greater than 3.0mm.

Comments from Referees:

Chapter 3.41 Also, different notations would be also required: I suggest using the indexes from previous chapters as CRUN/PIT in eq 10 and CRSA/PIT in eq 11.

Author's response: Ok.

Author's changes in manuscript: These have been changed as shown above.

Comments from Referees:

Chapter 3.42: The assumption used here is that the gauge ratios for mixed precipitation vs wind relation is linear. In the Goodison et al (1998) WMO reference (page 28) the relationship can be much more complex for different types of snow events (dry, wet).

Author's response: This equation has been revised by using new data updated to April 30 2015. But in our field, the dry or wet event are not observed.

Author's changes in manuscript: The new equations are shown in Table 4, Fig.6 and in Eqs. (12) ~ (17). This part has been revises as following:

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 α<0.10, whereas for the $CSPG_{SA}$, the Eq.(13) doesn't pass but has a α value of about 0.16 (Table 4).

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

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

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

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

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

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

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

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

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

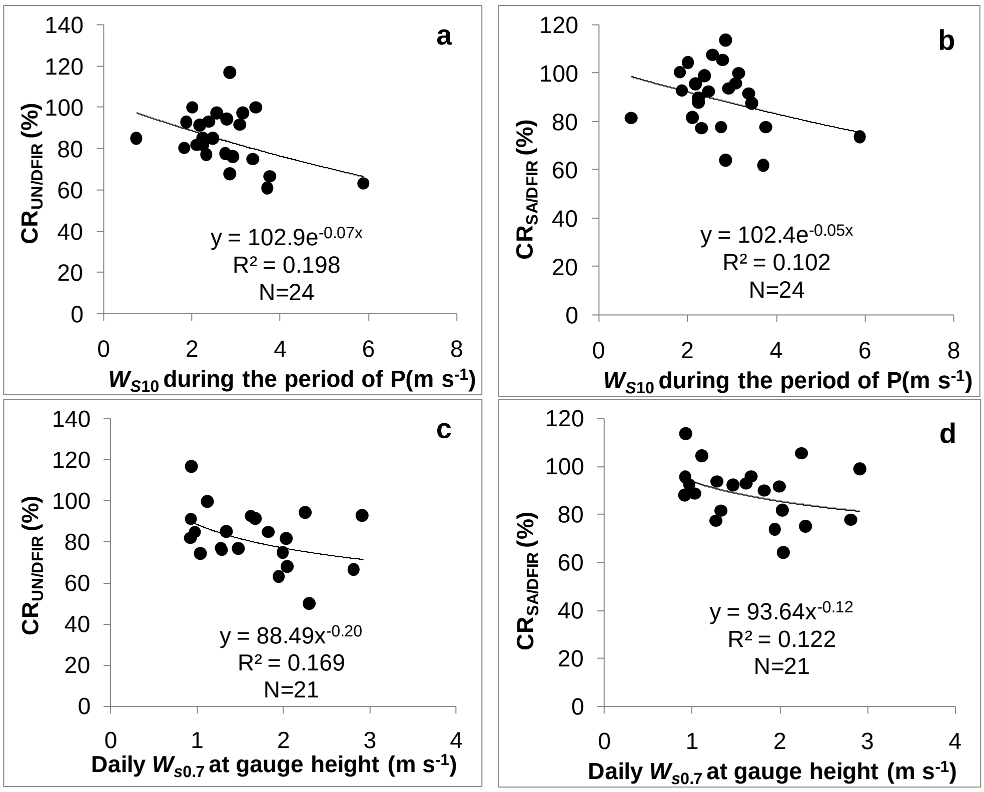


Figure 6. Catch ratios (CRs) vs. wind speed for the mixed precipitation event (**a** and **b**) and the daily mixed precipitation (**c** and **d**) greater than 1.0mm.

Comments from Referees:

Chapter 3.42: The suggested notations are CRUN/DFIR in eq 12 and CRSA/DFIR in eq 13.

Author's response: Ok.

Author's changes in manuscript: Please see the revision shown above.

Comments from Referees:

Chapter 3.43: The assumption used here is that the gauge ratios for snowfall vs wind relation is linear. In the Goodison et al (1998) WMO reference the relationship can be.

Author's response: These equations have been revised by using new data updated to April 30 2015.

Author's changes in manuscript: The new equations are shown in Table 4, Fig.7 and in Eqs. (18) ~ (23). This part has been revises as following:

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 $\alpha<0.001$. The Eq.(18) is similar with the Eq.(5) suggested by Yang et al. (1991). For the $CSPG_{SA}$, the power law expression Eq.(19) passes the F-test when $\alpha<0.05$ (Table 4).

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

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

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

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

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

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.

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

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

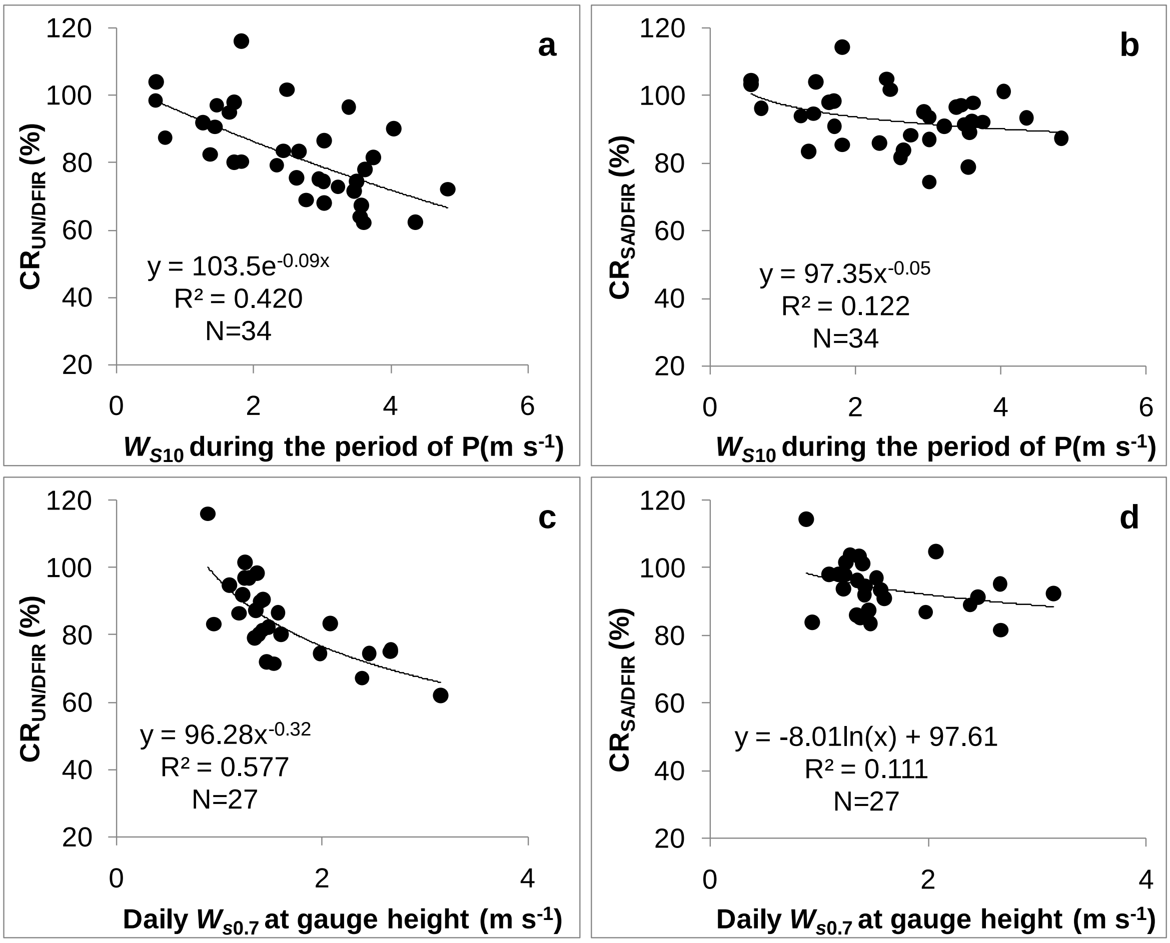


Figure 7. Catch ratios (CRs) vs. wind speed for the snowfall event (**a** and **b**) and the daily (**c** and **d**) snowfall greater than 1.0mm.

Comments from Referees:

Chapter 3.43: The suggested notations are CRUN/DFIR in eq 12 and CRSA/DFIR in eq 13.

Author's response: Ok.

Author's changes in manuscript: Please see the revision shown above.

Comments from Referees:

Chapter 4.2 In the given experiment CSPGPIT > CSPGDFIR was true for rain and mixed precipitation, the catch ratio is only a consequence of this fact. The CSPGPIT can be used as reference, but it is not better than CSPGDFIR observations.

Author's response: It's true. In the revised paper, the $CSPG_{DFIR}$ is the only reference to calculate the CRs.

Author's changes in manuscript: In the Table 4, Fig.5~Fig.7 and Eqs.(10)~(23) and the whole text, these kind of description had been revised.

Comments from Referees:

P2213/L8: Sentence “Scarcity: : :” it is not true generally, please remove sentence.

Author's response: Ok.

Author's changes in manuscript: This sentence has been deleted.

Comments from Referees:

P2213/L9: What is the final suggestion for reference? CSPGPIT or CSPGDFIR ? Under which circumstances Please clarify.

Author's response: $CSPG_{DFIR}$ is undoubtedly the reference. But it is expensive and should be installed far from the Chinese national meteorological stations, or it will affect the meteorological observation. In the most regions in China were the snowfall and blowing snow is little relatively, the $CSPG_{PIT}$ may be a good choice. Whereas in other regions, it should use CSGPDFIR.

Author's changes in manuscript: This part has been revised as:

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.

Comments from Referees:

P2213/L15: The authors compare the configurations from most to least rain and mixed precipitation (not the catch ratio), so the relation should be: CSPGPIT > CSPGDFIR > CSPGSA > CSPGUN . (What would CRDFIR mean otherwise?)

Author's response: ok.

Author's changes in manuscript: This part has been revised as:

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: $CSPG_{DFIR}$ > $CSPG_{PIT}$ > $CSPG_{SA}$ > $CSPG_{UN}$.

In the ABSTRACT, it also been revised.

Comments from Referees:

P2213/L17: Similarly, from most to least snowfall the relation should be: CSPGDFIR > CSPGPIT > CSPGSA > CSPGUN .

Author's response: ok.

Author's changes in manuscript: It also revised as shown above.

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

Anonymous Referee #2 First

Received and published: 11 May 2015

Comments from Referees:

At beginning, I do not agree to first sentence of abstract "Systematic errors in gauge measured precipitation are well-known but no reports have come from the Tibet Plateau"! Yes, it is important issue, but there have a lot of reports on bias correction in Tibet. It is clear that we may not able perform experimental observation at everywhere on the world, but we could correct bias employee the procedure recommended By WMO, in which the correlation of various loss to the climatic parameters have been dressed. What we should pay attention is that classification of precipitation type, say rain, snow or mix, that formulas is deal to be local due to it relating to the geophysical condition.

Had reviewing the present manuscript, the recommended procedure was clarified. It is fine we could improve the result. However, the formulas for classification of precipitation type, the result published on 1999 still using, that should be improved using local observation result.

Thereby, I would like to recommend the manuscript to published after major revision.

Anonymous Referee #2 Second

Received and published: 12 May 2015

Comments from Referees:

The author seem not understood my words. I know the WMO procedure could be improved, but it was just relating to the wind speed in theoretically. Generally, the equ. must be suitable for anywhere you using similar data. As well, I knew the the equ. was gained in Tianshan region by huge field observations and improved many times.

Surely, you can improve it too. But it theoretically not local! What you should improve is that classification for precipitation-type, that is local due to the parameter in the emu. is variable. There is new publication by K Yang (may not 1st author), a new method has been developed. The author no need explain your classification again. Frankly the reviewer knew that very well. I note one of the co-author of manuscript is E Kang, I would like to suggest you discuss my words with E Kang.

Again, my comment: what you should pay attention is classification, for the other, you can do your work but it is not so necessary theoretically.

NOTE: These response are not the original responses to the Reviewer 2. This is the formal and last response to the two comments of the Reviewer 2.

Author's response: Thank you very much for your good advices. We have discussed your advices with all the authors including E Kang. This paper is badly written at present.

1) The sentence "Systematic errors in gauge measured precipitation are well-known but no reports have come from the Tibet Plateau" is really not accurate. There is no contrastive field experiment using $CSPG_{DFIR}$ as referee in the present literature, but there has built up some $CSPG_{DFIR}$ in recent years at some sites (for rainfall, the PIT has also been used and reported in Tibet in the past years), and there are several reports on bias correction by

using the WMO equations. We will correct the related description.

2) This paper is submitted to the special issue "The World Meteorological Organization Solid Precipitation InterComparison Experiment (WMO-SPICE) and its applications (AMTD/ESSDD/HESSD/TCD Inter-Journal SI)". From this point of view, we would pay more attention to the Intercomparison experiment results and their applications.

3) The WMO equations do not include CSPG adjustments equations for wind-induced errors. Yang et al. (1991) gave the Eqs. (5-7) by using wind data at Daxigou station, which is about 1.7 km far away from the experimental site: Although the Precipitation InterComparison Experiment for Chinese standard precipitation gauge (CSPG) had been conducted from 1987 to 1992 in Tianshan, and many valuable data have been acquired, the wind data are lack owing to the contemporary economy condition (Yang et al., 1991; Goodison et al., 1998). From Goodison et al.(1998), there is no calibration equations like Eqs. (2-4) for CSPG. Yang et al. (1991) gave the Eqs. (5-7) by using wind data at Daxigou station, which is about 1.7 km far away from the experimental site. Ren and Li (2007) have observed 29,000 precipitation events data from 30 stations all over China, whereas the DFIR has not been used. After that, from the literatures, several reports have provided the precipitation bias-error correcting method in China such as Ye et al. (2004, 2007), Ma et al. (2014), they also used the Eqs. (5-7) for CSPG.

Therefore, the wind-induced error of CSPG has not been well tested. Here we firstly compare the precipitation measured by CSPG with different shields, then we would use our observation data till to April 2015 to establish two kinds of calibration equations for CSPG. One is for easy application by using 10m-height wind speed in China, another is similar to the Eqs. (2-4) on daily scale. From the WMO procedure and your advices, this kind of equations may be widely used. It may be the improvement of Eqs. (5-7).

4) Precipitation type classification is very important especially in the distributed hydrological models. In the several precipitation bias-error adjusting methods, the precipitation type is firstly classified then the calibration equations for different precipitation type is used. As you have recommended, K Yang's (2014) method is widely accepted. They have used observed data all over China. Our observation data are just from one site which is located near the Qilian and Yeniugou station that have been used by K Yang et al (2014). I am not sure whether the parameter from one site is so important.

We would describe relevant contents in the Chapter 2.1 INTERCOMPARISON EXPERIMENTS AND RELEVANT DATA and other parts.

Author's changes in manuscript: From your advices and the Reviewer 1's comments, the paper has revised majorly as follows:

1) The first sentence in the ABSTRACT has been revised as: 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.

2) The third and fourth paragraphs of the INTRODUCTION part has been revised largely as:

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

used the adjusted equations from 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 CSPGs.

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

3) The precipitation phase discrimination methods are revised in 2.1 INTERCOMPARISON EXPERIMENTS AND RELEVANT DATA:

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

In the Chapter 4.3 UNCERTAINTIES OF THE EXPERIMENT, it also discussed:

In this field experiment, the precipitation phase is also discriminated by the observers. This method is somewhat rough though it has been the standard way since the 1950s at the CMA stations.

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

Anonymous Referee #3

Received and published: 4 June 2015

Comments from Referees:

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.

Author's response: 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:

1) Data are updated to April 30 2015;

2) Abstract, Introduction, Data and method, Results and Discussion, Tables, Figures and Equations etc. are

majorly revised.

After revision, the adjustment equations have been carefully considered.

Author's changes in manuscript: For example, the equations are partly summarized in the Table 4.

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

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

4 *: 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).

Comments from Referees:

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).

Author's response: We have revised it according to the Reviewer 1's advices. The terms of $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ have been used. The nomenclature 'catch ratio' is wrongly used before in the abstract and in the text.

Author's changes in manuscript: In the ABSTRACT, the sentence has been added: The $CSPG_{DFIR}$ is used as reference to calculate the catch ratios (CRs) of the $CSPG_{UN}$, $CSPG_{SA}$ and $CSPG_{PIT}$.

Comments from Referees:

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?

Author's response: 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, another snow collector is used to replace the present using one, and the using one is weighted by an electronic balance 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.

Author's changes in manuscript: This sentence has been added: "If there is frost on the outside surface of the collector, it will be wiped up by using a dry hand towel. In the rare cases of snowfall accumulating on the rim of the collector, half of them (semi circular) will be removed before they are weighted. ".

Comments from Referees:

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?

Author's response: 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).

Author's changes in manuscript: This part has been revised as:

2.2 Adjustment methods

This field experiment focuses on two key aspects. One is comparisons among the $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$. Another purpose is to establish adjustment equations for the $CSPG_{UN}$ and the $CSPG_{SA}$ by using the $CSPG_{DFIR}$ as reference. To adjust the gauge-measured precipitation, Sevruk and Hamon (1984) have given the general formula as:

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

Where P_c is the adjusted precipitation, K is the wind-induced coefficient and P_g is the gauge-measured precipitation. P_w is the wetting loss, P_e is the evaporation loss, P_t is trace precipitation and P_{DFIR} is DFIR-shielding precipitation. For the CSPG, P_w is 0.23 mm for rainfall measurements, 0.30 mm for snow and 0.29 mm for mixed precipitation (Yang, 1988; Yang et al., 1991), according to the measurements in the Tianshan valley site. Ren and Li (2007) reported a mean value as about 0.19 mm for total precipitation over eastern China. The CSPG design reduces P_e to a value smaller than other losses in the warm, rainy season (Ye et al., 2004; Ren and Li, 2007). In winter, P_e is already small (0.10–0.20 mm/day) according to results in Finland (Aaltonen et al., 1993) and Mongolia (Zhang et al., 2004). To prevent evaporation loss in Chinese operational observations on some particular days, e.g., hot and dry days or days of snow, precipitation is measured as soon as the precipitation event stops (CMA, 2007a; Ren and Li, 2007). A precipitation event of less than 0.10 mm is beyond the resolution of the CSPG and is recorded as a trace amount of precipitation (P_t). Ye et al. (2004) recommended assigning a value of 0.1 mm, regardless of the number of trace observations per day.

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

The WMO has given Eqs.(2)-(4) for the shielded Tretyakov gauge catch ratio versus daily wind speed (W_s, m s^{-1}) at gauge height, and daily maximum and minimum temperatures (T_{max}, T_{min}, °C) on a daily time step for various precipitation types (Yang et al., 1995; Goodison et al., 1998). These equations can be used over a great range of environmental conditions (Goodison et al., 1998). Therefore, in this paper, the catch ratio (*CR*, %) follows their definition by using $CSPG_{DFIR}$ as reference.

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

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

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

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

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

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

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

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

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

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

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

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

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

Where Z is 0.7 m or 10 m.

Comments from Referees:

What is the frequency of each type of observation (precipitation, wind speed, temperature)? This is important in terms of how representative the conditions are for each measurement.

Author's response: Each type of observation in the meteorological tower is observed every 30 seconds, and they are saved every half an hour (mean or sum).

Author's changes in manuscript: The following sentences have been added: 'They are observed every 30 seconds and are saved as half-hourly values (sum or mean).'

Comments from Referees:

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.?

Author's response: 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.

Author's changes in manuscript: 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. Based on the CSPG measurements, several methods of phase discrimination have been reported, such as the air temperature index method (e.g. Zhang et al., 2004; Ye et al., 2004; Chen et al., 2014b), dew point index method (e.g. Chen et al., 2014b), and the new wet bulb temperature index method (Ding et al., 2014). However, the parameters of these method vary largely in spatial, and their reference precipitation phase data are still from the CMA's stations. '

In the new Chapter **4.3 UNCERTAINTIES OF THE EXPERIMENT,** the following words are added:

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

Comments from Referees:

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?

Author's response: According to the Reviewer 1's advices, 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.

Author's changes in manuscript: This part has been revised as: "

3.1 Precipitation gauge intercomparison for rainfall

Good linear correlations are found among the four CSPG installments (Fig.2). From September 2010 to April 2015, the $CSPG_{PIT}$ caught 4.7% and 3.4% more rainfall than the $CSPG_{UN}$ and the $CSPG_{SA}$ respectively

(($CSPG_{PIT}$-$CSPG_{UN}$)/$CSPG_{UN}$*100; similarly hereinafter). The $CSPG_{SA}$ caught 1.3% more rainfall than the $CSPG_{UN}$ (Table 3).

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

Comments from Referees:

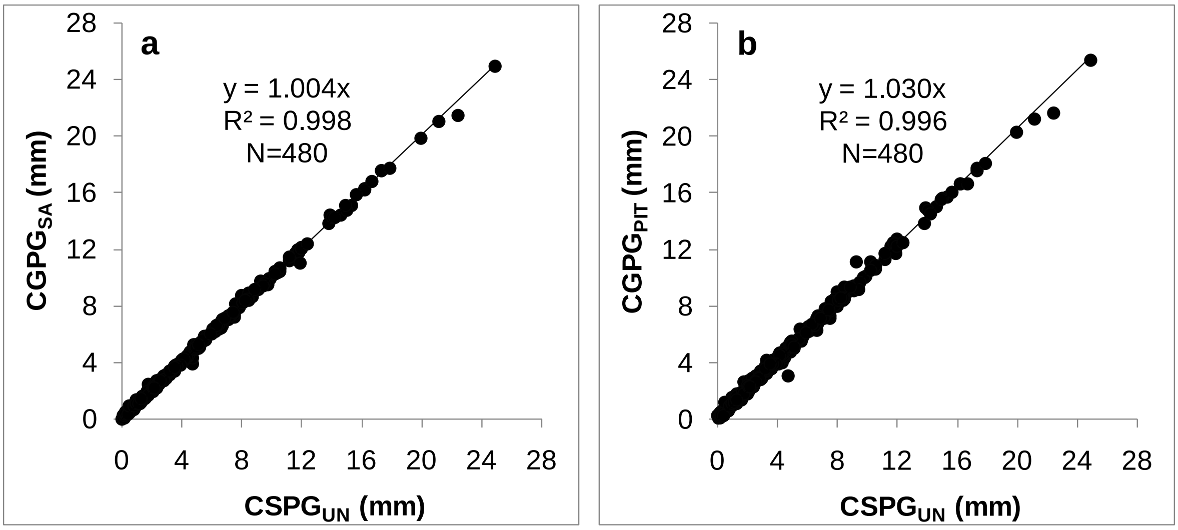
On P. 2208, lines 5-6, you note that 'comparative studies indicate that the Pit gauge CR is superior to that of the DFIR or the other gauges (Fig. 2)'. How is this clear from Fig. 2? I see a near 1:1 relationship between the Pit and DFIR configurations, and no comparison plots are shown for the CSPG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

Author's response: 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. The Fig.2 is also redrawn.

Author's changes in manuscript: The section 3.1 has been revised as described above. The Fig.2 and Table 3 are also revised:

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

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



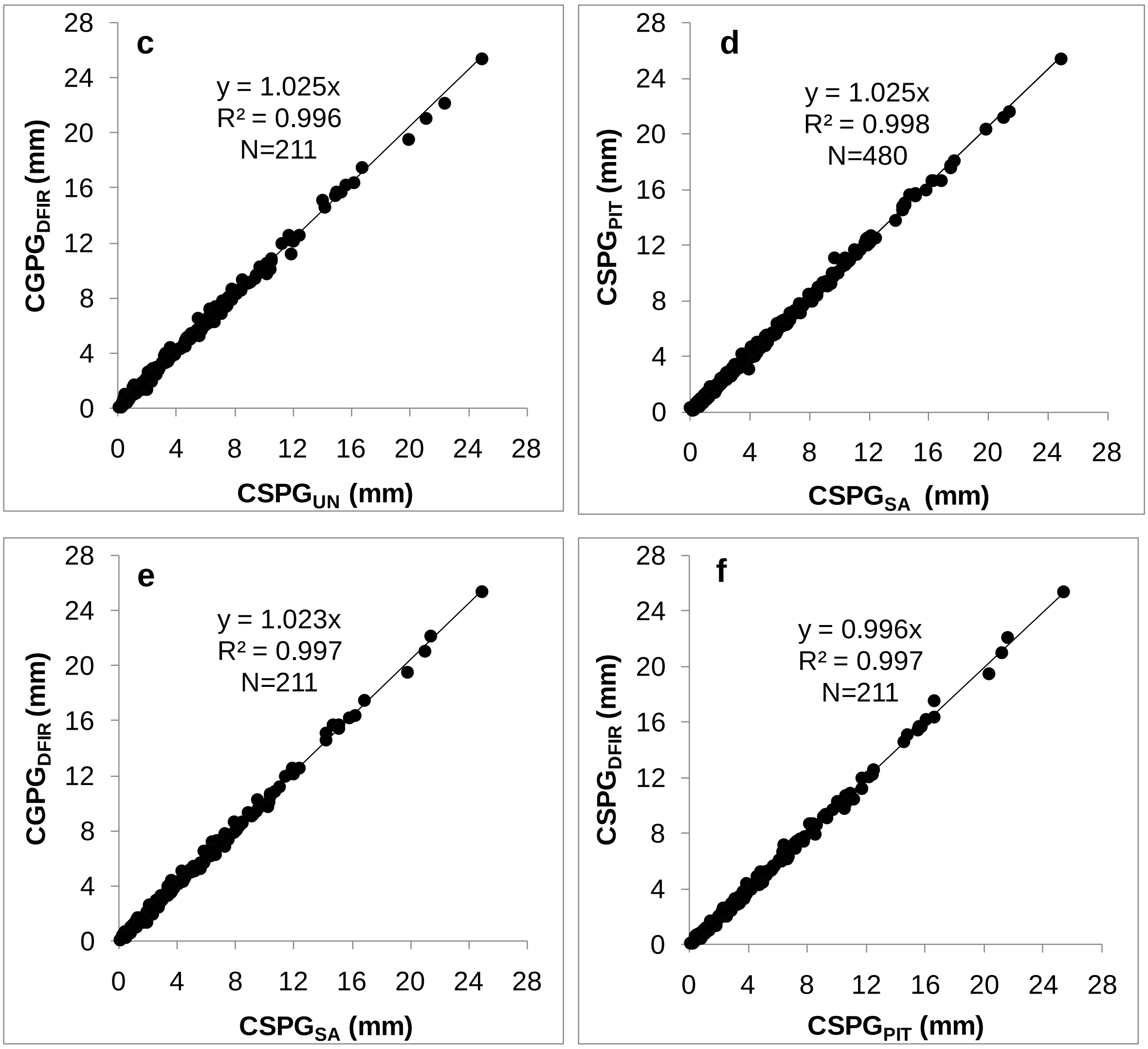


Figure 2. Intercomparison plots among $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ for the rainfall events from September 2010 (**a**, **b** and **d**) or September 2012 (**c**, **e** and **f**) to April 2015**.**

Comments from Referees:

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?

Author's response**:** All these kinds of statements are deleted in the revised version.

Author's changes in manuscript: The section 3.1 has been revised as shown above.

Comments from Referees:

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

Author's response**:** All these kinds of statements are deleted in the revised version.

Author's changes in manuscript: The section 3.2 has been revised as :

3.2 Precipitation gauge intercomparison for mixed precipitation

From September 2010 to April 2015, a total of 44 mixed precipitation events were observed. The $CSPG_{PIT}$ caught 12.1% and 5.6% more mixed *P* than the $CSPG_{UN}$ and the $CSPG_{SA}$, respectively. The $CSPG_{SA}$ caught 6.1% more mixed *P* than the $CSPG_{UN}$ (Table 3). From September 2012 to April 2015, the $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DIFR}$ caught 7.7%, 15.6% and 14.2% more mixed *P* than the $CSPG_{UN}$, respectively. The $CSPG_{PIT}$ and the $CSPG_{DFIR}$ caught more 7.3% and 6.0% mixed *P* than the $CSPG_{SA}$, respectively. Whereas the $CSPG_{DFIR}$ caught 1.2% less mixed *P* than the $CSPG_{PIT}$ (Table 3).

Good linear correlations are observed among the gauges (Fig.3). The $CSPG_{PIT}$ caught 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.

Comments from Referees:

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).

Author's response: 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.

Author's changes in manuscript: A new Table 4 are added:

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

Temporal scale	Phase	Gauges	Best catch ratio (CR) vs. wind speed relation*	P (mm)	No. of events	F-test
Precipitation event	Rain	$CSPG_{UN}$	$CR_{UN/DFIR,Rain} = 0.181W_{s10}^3 - 2.028W_{s10}^2 + 5.983W_{s10} + 92.24$ R^2=0.070	P>3.0	103	α=0.06
		$CSPG_{SA}$	$CR_{SA/DFIR,Rain} = 0.188W_{s10}^3 - 2.027W_{s10}^2 + 5.554W_{s10} + 94.27$ R^2=0.099			α=0.01
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Rain} = 0.150W_{s10}^3 - 1.748W_{s10}^2 + 6.183W_{s10} + 94.20$ R^2=0.023			α=0.50
	Mixed	$CSPG_{UN}$	$CR_{UN/DFIR,Mixed} = 102.9e^{-0.07W_{s10}}$ R^2=0.198	P>1.0	24	α=0.07
		$CSPG_{SA}$	$CR_{SA/DFIR,Mixed} = 102.4e^{-0.05W_{s10}}$ R^2=0.102			α=0.16
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Mixed} = -5.811\ln(W_{s10}) + 106.4$ R^2=0.023			α=0.47
	Snow	$CSPG_{UN}$	$CR_{UN/DFIR,Snow} = 103.5e^{-0.09W_{s10}}$ R^2=0.420	P>1.0	32	α=4.7E-5
		$CSPG_{SA}$	$CR_{SA/DFIR,Snow} = 97.35W_{s10}^{-0.05}$ R^2=0.122			α=0.04
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Snow} = 0.160W_{s10}^3 + 0.956W_{s10}^2 - 9.754W_{s10} + 109.9$ R^2=0.110			α=0.30
Daily precipitation	Rain	$CSPG_{UN}$	$CR_{UN/DFIR,Rain} = -1.400W_{s0.7}^3 9.403W_{s0.7}^2 - 18.22W_{s0.7} + 106.8$ R^2=0.045	P>3.0	90	α=0.26
		$CSPG_{SA}$	$CR_{SA/DFIR,Rain} = -0.924W_{s0.7}^3 + 6.525W_{s0.7}^2 - 13.47W_{s0.7} + 105.7$ R^2=0.031			α=0.43
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Rain} = -0.952W_{s0.7}^3 + 6.371W_{s0.7}^2 - 12.62W_{s0.7} + 108.4$ R^2=0.017			α=0.68
	Mixed	$CSPG_{UN}$	$CR_{UN/DFIR,Mixed} = 88.49W_{s0.7}^{-0.20}$ R^2=0.169	P>1.0	21	α=0.06
		$CSPG_{SA}$	$CR_{SA/DFIR,Mixed} = 93.64W_{s0.7}^{-0.12}$ R^2=0.122			α=0.12
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Mixed} = 101.6W_{s0.7}^{-0.05}$ R^2=0.017			α=0.60
	Snow	$CSPG_{UN}$	$CR_{UN/DFIR,Snow} = 96.28W_{s0.7}^{-0.32}$ R^2=0.577	P>1.0	27	α=5.7E-6
		$CSPG_{SA}$	$CR_{SA/DFIR,Snow} = -8.01\ln(W_{s0.7}) + 97.61$ R^2=0.111			α=0.09
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Snow} = -5.760W_{s0.7}^3 + 41.641W_{s0.7}^2 - 93.05W_{s0.7} + 160.5$ R^2=0.134			α=0.33

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

Comments from Referees:

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

Author's response: Ok.

Author's changes in manuscript: A total of 12 'calibrations ' or 'calibrate' are replaced.

Comments from Referees:

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.

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

Author's changes in manuscript: A new Table 4 are added as shown above. The text and equations are revised. Now a total of 14 effective equations are listed (Eqs. (10)-(23)).

Comments from Referees:

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.

Author's response: All these kinds of statements are deleted in the revised version. The figures are redrawn after data updated.

Author's changes in manuscript: The Fig.8 has been replaced by Fig.6:

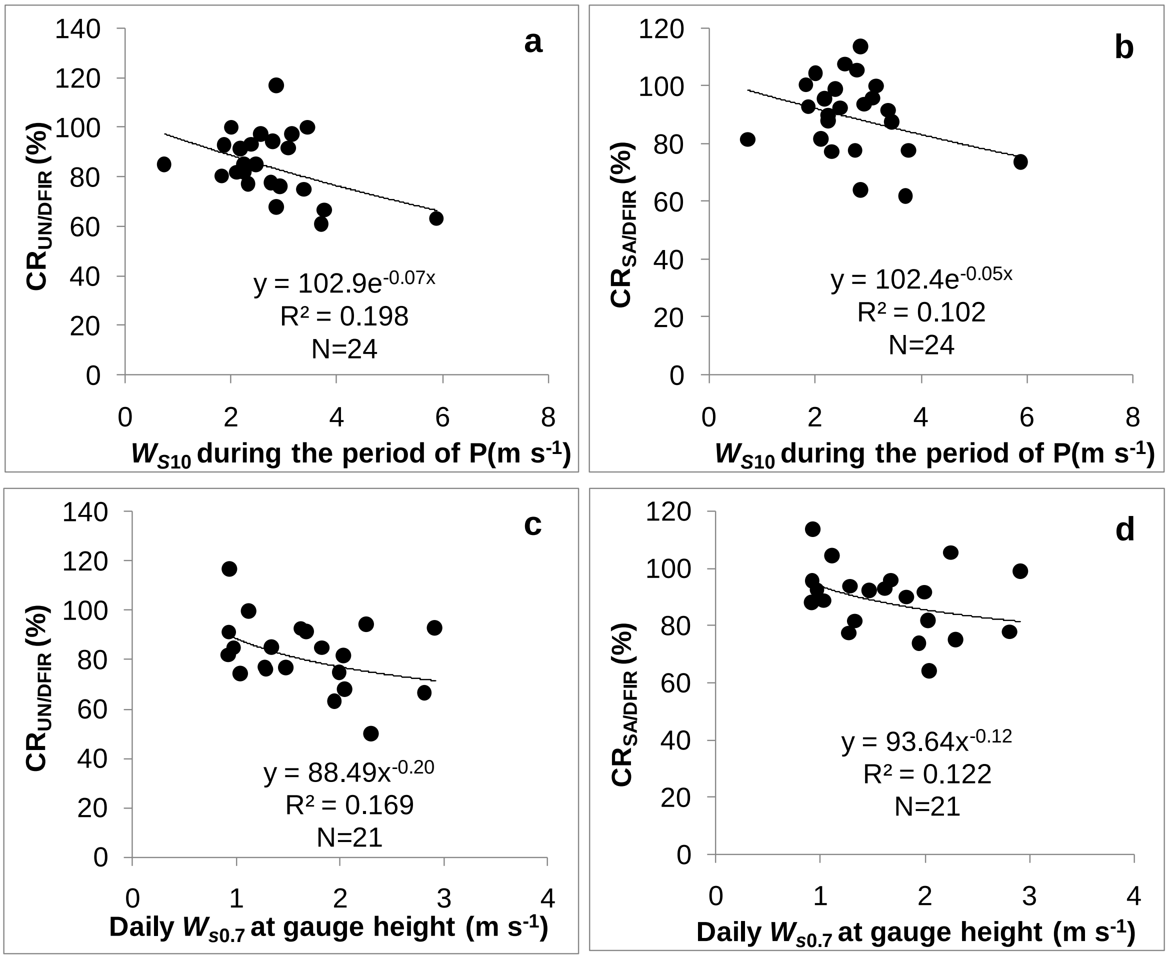


Figure 6. Catch ratios (CRs) vs. wind speed for the mixed precipitation event (**a** and **b**) and the daily mixed precipitation (**c** and **d**) greater than 1.0mm.

The section **"3.4.2 Mixed precipitation catch ratio vs. wind speed"** has been revised as:

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

0.16 (Table 4).

Fig.6 about here

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

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

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 a α value of about 0.12 (Table 4).

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

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

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.

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

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

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

Comments from Referees:

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

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

Author's changes in manuscript: It has been revises as shown above.

Comments from Referees:

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).

Author's response: They are revised.

Author's changes in manuscript: It has been revises as shown above.

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript:

Comments from Referees:

3. Proposed technical corrections

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

Author's response:**:** ok.

Author's changes in manuscript: 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).

Comments from Referees:

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

Author's response:**:** ok.

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

Comments from Referees:

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

Author's response:**:** ok.

Author's changes in manuscript: Rodda (1967) compared the catch of a UK 5″ manual gauge ...

Comments from Referees:

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

Author's response:**:** ok.

Author's changes in manuscript: the Double Fence International Reference (DFIR) shield with a Tretyakov shield was designated the reference standard snow gauges configuration (Goodison et al., 1998)

Comments from Referees:

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

Author's response:**:** ok.

Author's changes in manuscript: the Double Fence International Reference (DFIR) shield with a Tretyakov shield was designated the reference standard snow gauges configuration (Goodison et al., 1998)

Comments from Referees:

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

Author's response:**:** ok.

Author's changes in manuscript: It is revised as: ' Because automation of precipitation measurements are widespread '.

Comments from Referees:

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).

Author's response:**:** ok.

Author's changes in manuscript: It is revised as: 'the WMO-SPICE project still selected DFIR shield as part of the reference configurations.'

Comments from Referees:

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

Author's response:**:** ok.

Author's changes in manuscript: It is revised as: ' Annual precipitation is about 447.2 mm during 2010-2012 and precipitation occurs most frequently during the warm season from May to September at this site.'

Comments from Referees:

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

Author's response:: ok.

Author's changes in manuscript: It is revised as: ' The DFIR shield has been operated as part of reference configurations at 25 stations in 13 countries around the world (Golubev, 1985; Sevruk et al., 2009), but deviations from the DFIR measurements vary by gauge type and precipitation type (Goodison et al., 1998). '

Comments from Referees:

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

Author's response:: ok.

Author's changes in manuscript: 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),

Comments from Referees:

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

Author's response:: ok.

Author's changes in manuscript: CSPG catch ratio equations were based on the 10 m height wind speed at the open Daxigou Meteorological

Comments from Referees:

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

Author's response:: ok.

Comments from Referees:

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

Author's response:: ok.

Author's changes in manuscript: rivers in China and neighboring countries, accurate precipitation data

Comments from Referees:

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

Author's response:: ok.

Author's changes in manuscript: accurate precipitation data are urgently needed.

Comments from Referees:

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

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

Comments from Referees:

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

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

Comments from Referees:

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

Author's response:**:** ok.

Author's changes in manuscript: 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 $CSPG_{SA}$).

Comments from Referees:

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

Author's response:**:** ok.

Author's changes in manuscript: The Single Alter shield (SA) is used by the CMA to enhance catch ratios of automatic gauges (Yang, 2014), so the SA shield was selected as another intercomparison configuration for the present study.

Comments from Referees:

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

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

Comments from Referees:

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

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

Author's changes in manuscript: The $CSPG_{DFIR}$ is the only reference.

Comments from Referees:

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

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

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript: watershed in the Qilian mountains, on the northeastern edge of Tibet Plateau, China

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript: Annual precipitation is about 447.2 mm during 2010-2012 and is concentrated during the warm season from May to September at this site.

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript: It has been revised throughout the manuscript according to the Reviewer 1's advices.

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript: The intercomparison experiments included (1) an unshielded CSPG ($CSPG_{UN}$; orifice diameter=20 cm, height=70 cm), (2) single Alter shield around a CSPG ($CSPG_{SA}$), (3) a CSPG in a pit ($CSPG_{PIT}$), and (4) a DFIR shield with a Tretyakov-shielded CSPG ($CSPG_{DFIR}$) (Fig.1, Table 2).

Comments from Referees:

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

Author's response: ok.

Comments from Referees:

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

Author's response: ok.

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript: P_w is the wetting loss, P_e is the evaporation loss,

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript: P_w is 0.23 mm for rainfall measurements, 0.30 mm for snow and 0.29 mm for mixed

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript: The CSPG design reduces P_e to a value smaller than other losses in the warm, rainy season

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript: regardless of the number of trace observations per day.

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript: Wind may be the most important factor influencing precipitation measurement in high mountain conditions.

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript: This field experiment focuses on two key aspects. One

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript: observation comparisons

Comments from Referees:

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

Author's response: ok. Precipitation events are added to 608.

Author's changes in manuscript: 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).

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript: A total of 8 'happened' are replaced.

Comments from Referees:

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

Author's response: Ok.

Author's changes in manuscript: This sentence is deleted in the new version.

Comments from Referees:

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?

Author's response: 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 $CSPG_{PIT}$ and $CSPG_{DFIR}$. Thus, data only can be compared from Sept. 2010 to Sept. 2014.

Author's changes in manuscript: In the new revised version, this question has been revised in the whole manuscript. Fig.2 is revised as shown above.

Comments from Referees:

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

Author's response: ok. Reviewer 1 also give this advice.

Author's changes in manuscript: A total of 3 "liner" has been corrected.

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript: This sentence has been deleted according to your above and Reviewer 1's advices.

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript: Section 3.2 has been rewritten. All the arbitrary words are deleted. This sentence has also been deleted.

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript: This part has been revised according to your above and Reviewer 1's advices. This sentence has also been deleted.

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript: This part has been revised according to your above and Reviewer 1's advices.

This sentence has also been deleted.

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript: This part has been revised according to your above and Reviewer 1's advices. This sentence has also been deleted.

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript: From September 2010 to April 2015, a total of 44 mixed precipitation events were observed.

Comments from Referees:

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

Author's response: ok.

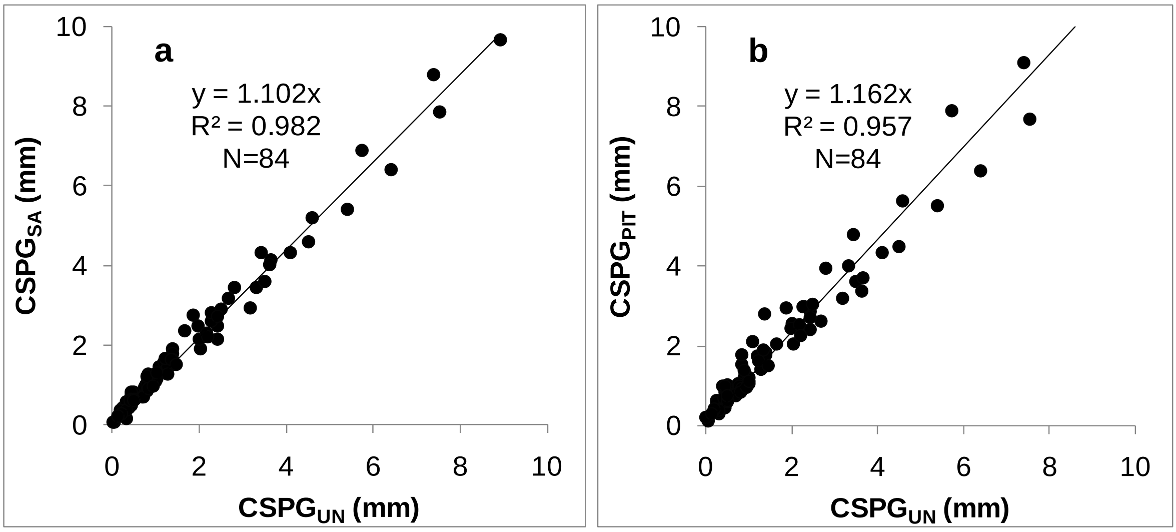
Author's changes in manuscript: Good linear correlations are observed among the gauges (Fig.3).

Comments from Referees:

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

Author's response: ok. Fig.5 has been changed as Fig.4.

Author's changes in manuscript: From Fig.4f, there is a linear correlation existed between the $CSPG_{PIT}$ and the $CSPG_{DFIR}$ ($CSPG_{DFIR}$=1.029$CSPG_{PIT}$, R^2=0.994).



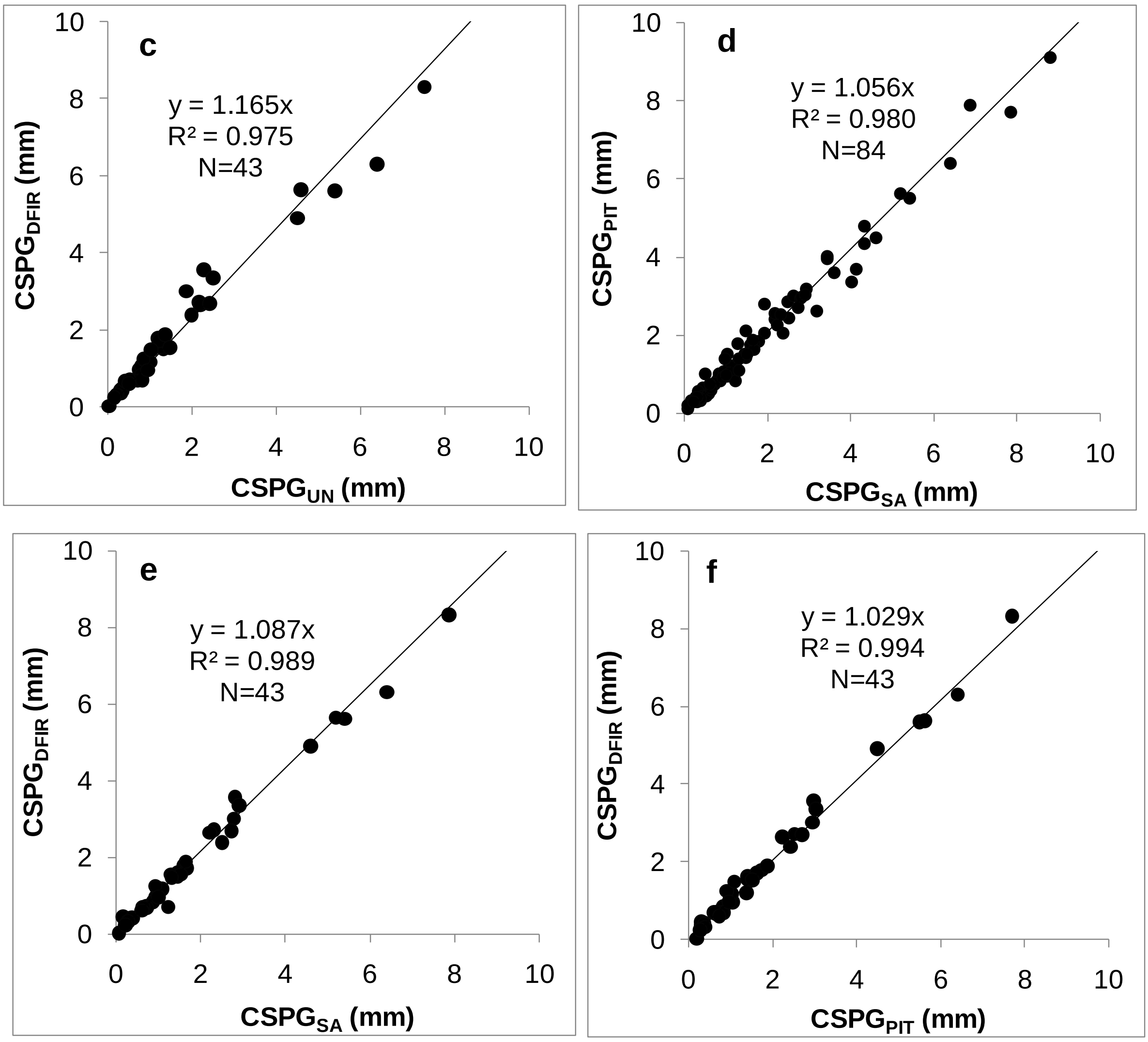


Figure 4. Intercomparison plots among $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ for the snowfall events from September 2010 (**a**, **b** and **d**) or September 2012 (**c**, **e** and **f**) to April 2015**.**

Comments from Referees:

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

Author's response: ok.

Author's changes in manuscript: This suggests that the $CSPG_{PIT}$ could be used as the reference gauge for snow precipitation events at the experiment site.

Comments from Referees:

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’

Author's response: ok.

Author's changes in manuscript: In the Hulu watershed, the ratios of $CSPG_{DFIR}/CSPG_{UN}$ for snowfall and mixed precipitation were 1.165 (Fig.4c) and 1.072 (Fig.3c), and the ratios of $CSPG_{PIT}/CSPG_{UN}$ for snowfall and mixed precipitation were 1.162 (Fig.4b) and 1.082 (Fig.3b), respectively.

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

M. Wolff (Referee)
mareilew@met.no
Received and published: 4 June 2015

Comments from Referees:

Precipitation measurements intercomparison in the Qilian Mountains, Northeastern Tibetan Plateau” by R. Chen et al. presents a 4-year data series from four different precipitation sensor configurations. The standard Chinese manual precipitation gauge CSPG in its original configuration was compared with the same gauge in a pit gauge configuration, inside a DFIR-shield (similar constructed as the WMO-recommended Double Fence Intercomparison Reference) and with a single Alter shield. Accumulation scatter plots, catch ratios for the whole time series as well as catch ratios per event are shown. Special attention is drawn to the comparability of the pit gauge configuration with the double fence configuration and the authors argue that the pit gauge could act as a reference of equal or better quality than the usual double fence reference.

The presented data set is indeed valuable as precipitation measurements with the possibility to compare to reference set ups are generally sparse. The wide use of the Chinese standard gauge CSPG in China justifies further tests of its performance and the evaluating of possible adjustment functions and their ability to improve standard precipitation measurements performed by this gauges is of interest. Furthermore, the evaluation of the pit gauge as a reference for sites with low annual snow cover and very limited blowing snow is valuable.

Within the WMO Solid Precipitation Intercomparison Experiment (SPICE) a number of precipitation gauges are currently tested, but additional studies on evaluations of those or other gauge configurations are very welcome as they will add to our knowledge about precipitation measurements. Thus, significant results of the presented study fit into the special issue “The World Meteorological Organization Solid Precipitation InterComparison Experiment (WMO-SPICE) and its applications” (AMTD/ESSDD/HESSD/TCD Inter-Journal SI)".

However, the described analysis methods, the presented results and discussions in this manuscript are in a rather premature state and the drawn conclusions are partly speculative. I encourage the authors to perform further analyses on their data and to revise their manuscript substantially.

Author's response: Thank you very much for your good advices.

Author's changes in manuscript: After three Reviewer's advices, now the manuscript has been majorly revised and been improved. Major revisions include:

1) The data are updated till April 30 2015, so the precipitation events especially the snowfall and mixed events are added which improves the certainties of the correlations between catch ratio and wind speed;

2) The CSPG with a DFIR shield is used as the only reference;

3) Best relationship are found between catch ratio and wind speed, and their probabilities are tested by F-test;

4) Two kinds of adjusting equations are established. One is for easy application by using 10m-height wind speed during the period of precipitation in China. Another type is similar to Eqs.(2)-(4), which use daily mean wind speed at gauge height (0.7m);

5) The Abstract, Introduction, Data and Methods, Results and Discussion, and Conclusions are all rewritten. Tables and Figures are redrawn. Some references are added. Two figures are deleted, whereas a new important Table 4 is added.

6) A new section '4.3 Uncertainties of the experiment' is added.

Comments from Referees:

General comments:

Abstract: The abstract contains a lot of details and very little general information about the background and goals of the study. It is not written very clear and needs substantial improvement The word calibration is not used correctly. As no absolute truth is known you are hardly able to calibrate your precipitation measurements, but rather correct or adjust them. I suggest replacing “calibration equation” with “adjustment equation” and “calibration” with “adjustment”.

Author's response: Thank you very much for your good advices.

Author's changes in manuscript: 1) The first sentence is rewritten as: '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.' ; 2) All the 'calibration ' and 'corrected' are replaced as 'adjustment ' or 'adjusted' according to your and Reviewer 3's advices.

Comments from Referees:

You refer to two sets of adjustment equations for the CSPG by Goodison et al. (1998) and Yang et al. (1991, 1995) and state an uncertainty connected to these equations without applying the equations to your data or comparing them to your adjustment functions. Your results and the results from Yang et al (1991) are very similar (as presented in subsection 4.1), which can be also supported by the similar climatology of these sites and their relative proximity. It remains unclear why you see the need for developing new equations Comparison with other studies.

It is neither documented why your equations should be superior to the cited equations. Instead of developing a new set of equations, it would be very valuable to thoroughly test and evaluate the existing equations with your dataset. And only in cases of obvious discrepancies you should start the effort of trying to improve the earlier suggested adjustments.

Author's response: This question has been described clearly in the revised versions. Yang et al. have conducted systematic precipitation intercomparison experiments and observed huge and valuable data at the Tianshan site. Because of the contemporary economy conditions during 1987-1992, there are no observed wind speed data at the Tianshan site. The used wind speed data are observed at Daxigou station (Yang et al., 1991). The distance is about 1.7km between the Tianshan site and Daxigou site, which would induce some uncertainties.

Author's changes in manuscript: The third paragraph of the Introduction is revised as :

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

Comments from Referees:

Your chapter “Data and methods” is combining information about the geography and climatology of the site, instrumentation and layout, measurement techniques, data corrections and the existing adjustment functions from other authors. I suggest dividing into several subsections with appropriate names.

Author's response: Thank you very much. In the revised version, we rewire this chapter: 2.1 Intercomparison experiments and relevant data; 2.2 Adjustment methods. Some descriptions are changed. The text are adjusted and improve.

Author's changes in manuscript:

2 Data and Methods

2.1 Intercomparison experiments and relevant data

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

The intercomparison experiments included (1) an unshielded CSPG ($CSPG_{UN}$; orifice diameter=20 cm, height=70 cm), (2) single Alter shield around a CSPG ($CSPG_{SA}$), (3) a CSPG in a pit ($CSPG_{PIT}$), and (4) a DFIR shield with a Tretyakov-shielded CSPG ($CSPG_{DFIR}$) (Fig.1, Table 2). The $CSPG_{UN}$, $CSPG_{SA}$ and $CSPG_{PIT}$ were installed before September 2010, whereas the $CSPG_{DFIR}$ was installed in September 2012 (Table 2). In the cold season (October to April), snowfall dominated the precipitation events, and in the warm season (May to September), rainfall dominated. The precipitation amount (P) is measured manually twice a day at 08:00 and 20:00 LT (Beijing time) according to the CMA's criterion (CMA, 2007a). In the warm season, P is measured by volume. In the cold season, the funnel and glass bottle are removed from the CSPG and precipitation is weighed under a windproof box to avoid wind effects. If there is frost on the 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. Based on the CSPG measurements, several methods of phase discrimination have been reported, such as the air temperature index method (e.g. Zhang et al., 2004; Ye et al., 2004; Chen et al., 2014b), dew point index method (e.g. Chen et al., 2014b), and the new wet bulb temperature index method (Ding et al., 2014). However, the parameters of these methods vary largely in spatial, and their reference precipitation phase data are still from the CMA's stations.

Relevant variables such as air temperature (maximum and minimum; T_{max} and T_{min}) have been observed manually at the site since June, 2009. A tower is used to measure wind speed (Lisa/Rita, SG GmbH; W_s) and air temperature (HMP45D, Vaisala) at 1.5m and 2.5m heights in association with relative humidity (HMP45D, Vaisala) and precipitation (Chen et al., 2014). They are observed every 30 seconds and are saved as half-hourly values (sum or mean). The specific meteorological conditions at the site are summarized in Table 1.

Fig.1 about here

Table 1 and Table 2 about here

2.2 Adjustment methods

This field experiment focuses on two key aspects. One is comparisons among the $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$. Another purpose is to establish adjustment equations for the $CSPG_{UN}$ and the $CSPG_{SA}$ by using the

$CSPG_{DFIR}$ as reference. To adjust the gauge-measured precipitation, Sevruk and Hamon (1984) have given the general formula as:

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

Where P_c is the adjusted precipitation, K is the wind-induced coefficient and P_g is the gauge-measured precipitation. P_w is the wetting loss, P_e is the evaporation loss, P_t is trace precipitation and P_{DFIR} is DFIR-shielding precipitation. For the CSPG, P_w is 0.23 mm for rainfall measurements, 0.30 mm for snow and 0.29 mm for mixed precipitation (Yang, 1988; Yang et al., 1991), according to the measurements in the Tianshan valley site. Ren and Li (2007) reported the mean P_w was about 0.19 mm for the total precipitation over eastern China. The CSPG design reduces P_e to a near-zero value smaller than other losses in the warm, rainy season (Ye et al., 2004; Ren and Li, 2007). In winter, P_e is already small (0.10–0.20 mm/day) according to the results in Finland (Aaltonen et al., 1993) and Mongolia (Zhang et al., 2004). To prevent evaporation loss in Chinese operational observations on some particular days, e.g., hot and dry days or days of snow, precipitation is measured as soon as the precipitation event stops (CMA, 2007a; Ren and Li, 2007). A precipitation event of less than 0.10 mm is beyond the resolution of the CSPG and is recorded as a trace amount of precipitation (P_t). Ye et al. (2004) recommended assigning a value of 0.1 mm, regardless of the number of trace observations per day.

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

The WMO has given Eqs.(2)-(4) for the shielded Tretyakov gauge catch ratio versus daily wind speed (W_s, m s^{-1}) at gauge height, and daily maximum and minimum temperatures (T_{max}, T_{min}, °C) on a daily time step for various precipitation types (Yang et al., 1995; Goodison et al., 1998). These equations can be used over a great range of environmental conditions (Goodison et al., 1998). Therefore, in this paper, the catch ratio (*CR*, %) follows their definition by using $CSPG_{DFIR}$ as reference.

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

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

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

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

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

Daxigou station:

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

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

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

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

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

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

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

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

Where Z is 0.7 m or 10 m.

Comments from Referees: The writing needs improvement. A complete language review of the manuscript needs to be performed by the author.

Author's response: We have improved the language in the revised manuscript. Some reviewers have also helped to improve the English.

Author's changes in manuscript: A language company has helped to improve the English.

Comments from Referees: Be consequent with denominator and nominator when using catch ratios. It is common to apply the reference as denominator.

Author's response: Thank you. We have found this error now. The Reviewer 1 has also pointed it out. They have been corrected in the revised version.

Author's changes in manuscript: In section **2.1 INTERCOMPARISON EXPERIMENTS AND RELEVANT DATA:** Therefore, in this paper, the catch ratio (*CR*, %) follows their definition by using $CSPG_{DFIR}$ as reference.

In all the equations, the CR is marked clearly, for example:

$$CR_{UN/DFIR,Mixed} = 102.9e^{-0.07W_{s10}}$$

Comments from Referees:

Specific comments:

Page 2203, line 9: Please check the height of the gauge, 30.5 m does not sound realistic

It is 30.5 cm. The Reviewer 1 has also pointed it out. Thank you.

Rodda (1967) compared the catch of a UK 5″ manual gauge exposed normally at the standard height of 30.5 cm above ground,

Comments from Referees:

Page 2203, line 11, line 13, line 14: Use the right and original references and cite appropriately for the three WMO-reports.

Author's response: Ok. We have changed them. In addition, the first WMO experiment is added.

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

Comments from Referees:

Page 2203, line 16: No need to use three references for the fact that the DFIR was used as reference during the WMO solid precipitation intercomparison by Goodison et al., 1998. The citation of the report is enough

Author's response: Ok. They are deleted both in the text and in the reference lists.

Author's changes in manuscript: See above paragraph.

Comments from Referees:

Page 2203, line 22 and line 28: Please add a reference for WMO-SPICE itself. Yang (2014) is related to the SPICE effort, but it cannot be used as “the” SPICE reference as Goodison et al. 1998 for the WMO solid precipitation intercomparison .

A SPICE website (http://www.wmo.int/pages/prog/www/IMOP/intercomparisons/SPICE/SPICE.html) exists, which can be used as a citation for SPICE. On the site you also find published meeting reports with relevant information and other publications related to SPICE. CIMO has also announced WMO-SPICE as an official program in their report.

Page 2203, line 25: Please find a more suitable publication for the reference in SPICE on the website, for example a TECO presentation related to SPICE references.

Author's response: Thank you very much. The "Yang, 2014" is replaced by the reference "Wolff, A. M., Nitu, R., Earle, M., Joe, P., Kochendorfer, J., Rasmussen, R., Reverdin, A., Sminth, C., Yang, D., and the SPICE-TEAM: WMO Solid Precipitation Intercomparison Experiment (SPICE): Report on the SPICE Field Working Reference System for precipitation amount, WMO, IOM No. 116, TECO-2014, World Meteorological Organization, Geneva, Switzerland, 2014."

Author's changes in manuscript: Because automation of precipitation measurements are widespread, the WMO Commission for Instruments and Methods of Observation (CIMO) organized the WMO Solid Precipitation Intercomparison Experiment (WMO-SPICE; Wolff et al., 2014) to define and validate automatic field instruments as references for gauge intercomparison, and to assess automatic systems and the operational networks for precipitation observations. The WMO-SPICE project still selected DFIR shield as part of the reference configurations.

Comments from Referees:

Page 2204, line 2: You are writing that additional attention must be paid to systematic errors of gauge measuring precipitation. I could not find any further description of systematic errors in your manuscript which are not already mentioned in Goodison et al (1998).

Author's response: ok.

Author's changes in manuscript: In these cold regions, solid precipitation often occurs and additional attention must be paid to wind-induced errors of gauge measured precipitation.

Comments from Referees:

Page 2205, line 3: state already here, that the 10 m wind speeds you are using are adjusted values from wind measurements at a different height.

Author's response: Yes, it's true. This is the bug of the experiment. Although the wind speeds are at 1.5 m and 2.5 m heights, they are observed at the same site as the precipitation intercomparison experiments.

Author's changes in manuscript: A new section **4.3 UNCERTAINTIES OF THE EXPERIMENT** is added, and its second paragraph is :

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

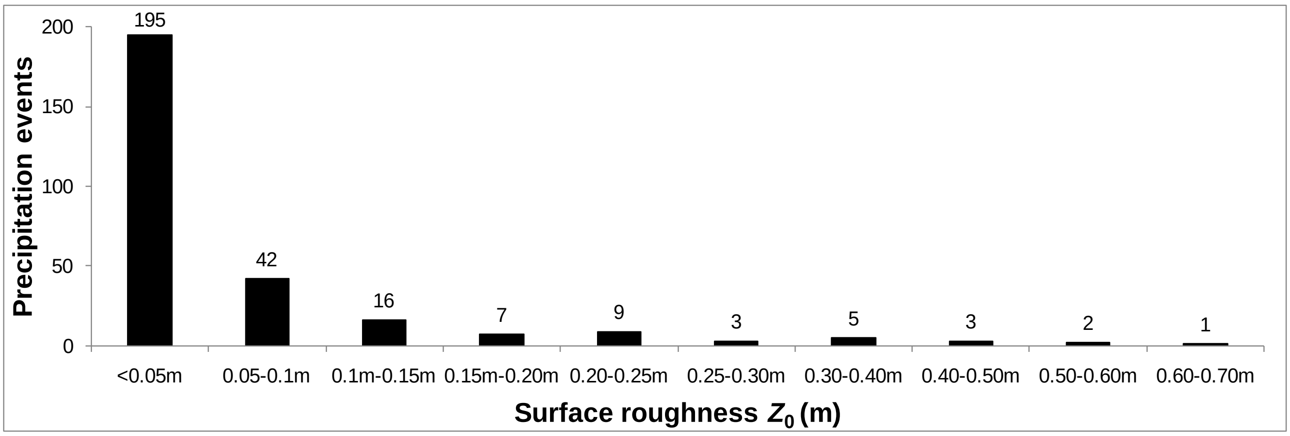


Figure 10. The surface roughness during the precipitation period from September 2012 to April 2015.

Comments from Referees:

Page 2206, lines 2-18: That section remains very unclear. Which of the corrections described are you applying? You cite concrete numbers for Pw (0.23 mm) and Pe (0.1-0.2mm, larger in summer). You describe Pe as very small although in the same order of magnitude as Pw, why? Are you adding Pt = 0.1 mm per day to compensate for trace events?

Page 2206, line9: do you mean that instead of calculating Pc, you can follow from equation 1, that PDFIR=K*Pg ? Please clarify.

Author's response: We will rewrite this part again. We want to say, the Pw, Pe and Pt etc. have been acquired by Yang et al. (1991), Ye et al. (2004) and Ren and Li (2007). Pe of CSGP is about zero for the rainfall. For the snowfall, to prevent evaporation loss in Chinese operational observations on some particular days, e.g., hot and dry days or days of snow, precipitation is measured as soon as the precipitation event stops (CMA, 2007a; Ren and Li, 2007). In this paper, we will not discuss them. Because only CSPG is used, the difference among the different installments ($CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$) are only caused by wind.

Author's changes in manuscript: This part has been rewritten as:

This field experiment focuses on two key aspects. One is comparisons among the $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$. Another purpose is to establish adjustment equations for $CSPG_{UN}$ and $CSPG_{SA}$ by using $CSPG_{DFIR}$ as reference. To adjust the gauge-measured precipitation, Sevruk and Hamon (1984) have given the general formula as:

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

Where P_c is the adjusted precipitation, K is the wind-induced coefficient and P_g is the gauge-measured precipitation. P_w is the wetting loss, P_e is the evaporation loss, P_t is trace precipitation and P_{DFIR} is DFIR-shielding precipitation. For the CSPG, P_w is 0.23 mm for rainfall measurements, 0.30 mm for snow and 0.29 mm for mixed precipitation (Yang, 1988; Yang et al., 1991), according to the measurements in the Tianshan valley site. Ren and Li (2007) reported a mean value as about 0.19 mm for total precipitation over eastern China. The CSPG design reduces P_e to a value smaller than other losses in the warm, rainy season (Ye et al., 2004; Ren and Li, 2007). In winter, P_e is already small (0.10–0.20 mm/day) according to results in Finland (Aaltonen et al., 1993) and Mongolia (Zhang et al., 2004). To prevent evaporation loss in Chinese operational observations on some particular days, e.g., hot and dry days or days of snow, precipitation is measured as soon as the precipitation event stops (CMA, 2007a; Ren and Li, 2007). A precipitation event of less than 0.10 mm is beyond the resolution of the CSPG and is recorded as a trace amount of precipitation (P_t). Ye et al. (2004) recommended assigning a value of

0.1 mm, regardless of the number of trace observations per day.

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

Comments from Referees:

Page 2206, equations 2,3,4: Are these equations developed for CSPG? If so, apply to your data and discuss the results

Author's response: They are not for CSPG. They are for shielded Tretyakov gauge. Here we want to use the forms of these equations for CSPG. In the revised version, the equations are given for the CSPG.

Author's changes in manuscript: The equations include:

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.

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

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

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

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.

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

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

Comments from Referees:

Page 2207, line 4: I assume that the equations 5,6,7 are from Yang et al., (1991). It remains unclear why are you citing Ye et al (2007). It seems, the latter was applying these equations, rather than developing them. You should note that.

Author's response: ok. Ye et al. (2007) has been deleted.

Author's changes in manuscript: The CMA stations usually observe wind speeds at 10 m height, so Yang et al.

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

Comments from Referees: Page 2207, lines 17-21: How do you define a precipitation observation? From later in the manuscript I understood that you were applying 3 mm in case of rain and 1 mm in case of snow and mixed precipitation as some threshold. Are these criteria applied for the 578 and 253 observations?

Author's response: They are precipitation events. In the section 3.1, 3.2 and 3.3, total precipitation events are intercompared. In the section 3.4, to decrease the CRs uncertainties caused by little precipitation, the threshold is used. The threshold is only used for 283 events from September 2012 to April 2015, because the reference $CSPG_{DFIR}$ is only observed during this period.

Author's changes in manuscript: In Table 3 and Table 4, it is clear in the revised version. Fig.2~Fig.4 now are also clear.

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

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

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

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

4 *: 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).

Comments from Referees: Page 2208, line 6. I don't agree with your conclusion from Figure 2, that the Pit gauge is superior to the DFIR. Both, the visual check and the regression data suggest that they are about equal, as you have to consider instrument uncertainties and scatter due to the nature of the precipitation events. I also think it is exaggerated to talk about comparative studies (plural), when you are showing only one scatter plot as an indicator. Further, a more thorough analysis should also consider wind and other dependencies. Are they still comparable within their uncertainty for different wind/temperature/other conditions?

Author's response: This part has been revised. Reviewer 1 and Reviewer 3 has also pointed it out.

Author's changes in manuscript: This part has been revised as:

3.1 Precipitation gauge intercomparison for rainfall

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

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

Comments from Referees:

Page 2208 line 12: I don't understand the sentence starting with "close line relationships: : :"

Author's response: Language problem.

Author's changes in manuscript: Good linear correlations are observed among the gauges (Fig.3).

Comments from Referees:

Page 2208, line 14: ": : : , which means: : :" is a rather strong statement. Try the words "suggest" or "indicate" or show more sound evidence

Author's response: It has been revised. Reviewer 3 has also pointed it out.

Author's changes in manuscript: This whole section has been rewritten. Relevant sentence: 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.

Comments from Referees:

Page 2208, line 18: The numbers are difficult to extract from Figures 4a and b. Please choose a different method to show these differences in a better way.

Author's response: Ok. It has been revised in the new Table 3. Reviewer 1 has also pointed it out.

Author's changes in manuscript:

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

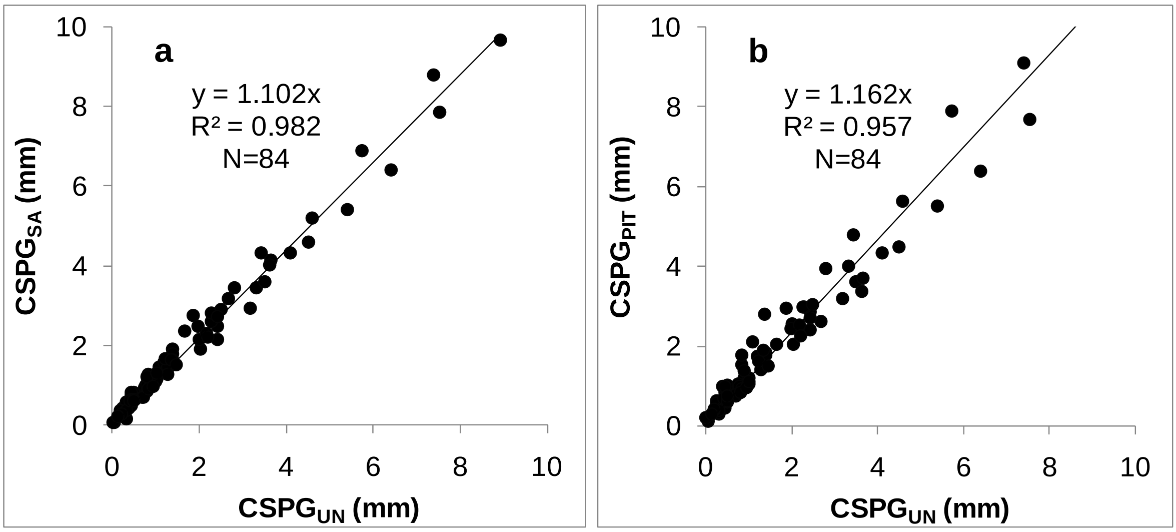
Date	Phase	No. of events	Total precipitation and catch ratio (CR, %)													
			$CSPG_{UN}$ (mm)	CR	$100\left(\frac{CSPG_{SA}}{CSPG_{UN}}-1\right)$	$100\left(\frac{CSPG_{PIT}}{CSPG_{UN}}-1\right)$	$100\left(\frac{CSPG_{DFIR}}{CSPG_{UN}}-1\right)$	$CSPG_{SA}$ (mm)	CR	$100\left(\frac{CSPG_{PIT}}{CSPG_{SA}}-1\right)$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

Comments from Referees:

Page 2208, line 18: There is definitely scatter in figure 4a and b.

Author's response: this figure has been redrawn after data updated to April 30 2015, and the results have been revised.

Author's changes in manuscript: The new Fig.4:



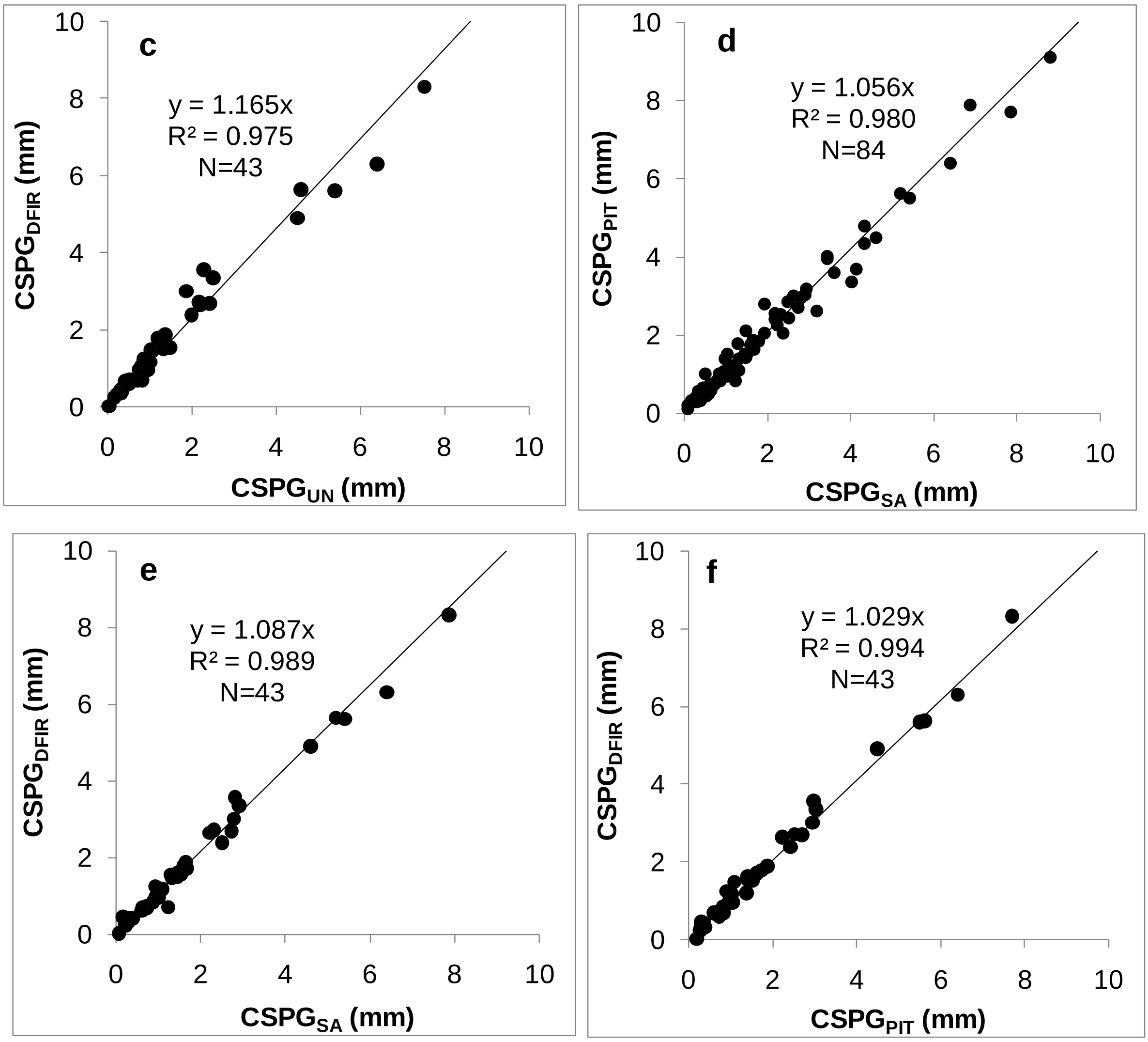


Figure 4. Intercomparison plots among $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ for the snowfall events from September 2010 (**a**, **b** and **d**) or September 2012 (**c**, **e** and **f**) to April 2015**.**

Comments from Referees:

Page 2208, line 21/22: It is not possible to follow your arguments. Please check your explanations on Page 2209, lines 7-10. That is a much better way to express why you use the pit gauge as a reference instead of the DFIR.

Author's response: Ok. All the RESULTS part has been rewritten.

Author's changes in manuscript: The relevant section is revised as following:

3.2 Precipitation gauge intercomparison for mixed precipitation

From September 2010 to April 2015, a total of 44 mixed precipitation events were observed. The $CSPG_{PIT}$ caught 12.1% and 5.6% more mixed *P* than the $CSPG_{UN}$ and the $CSPG_{SA}$, respectively. The $CSPG_{SA}$ caught 6.1% more mixed *P* than the $CSPG_{UN}$ (Table 3). From September 2012 to April 2015, the $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DIFR}$ caught 7.7%, 15.6% and 14.2% more mixed *P* than the $CSPG_{UN}$, respectively. The $CSPG_{PIT}$ and $CSPG_{DFIR}$ caught more 7.3% and 6.0% mixed *P* than the $CSPG_{SA}$, respectively. Whereas the $CSPG_{DFIR}$ caught 1.2% less mixed *P* than the $CSPG_{PIT}$ (Table 3).

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

Fig.3 about here

3.3 Precipitation gauge intercomparison for snowfall

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

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

Fig.4 about here

Comments from Referees:

Page 2209, lines 23-24: Did you use these thresholds for the analysis in the previous section as well? If yes, that information needs to be stated earlier, see comment above.

Author's response: No. The thresholds are only used for correlations between CR and wind speed.

Author's changes in manuscript: This part is revised as:

3.4 Catch ratio vs. wind speed

Previous studies showed that wind speed during the precipitation period is the most significant variable affecting gauge catch efficiency (Metcalfe and Goodison, 1993; Yang et al., 1995; Goodison et al., 1998). As described above, the wind-induced error of CSPG measurement has not been well tested. Because the CMA stations observe wind speeds at 10 m height, so the $CSPG_{UN}$ and the $CSPG_{SA}$ adjustment equations for single precipitation event are established with 10 m height wind speeds during the period of precipitation. On daily scale, the adjustment equations similar to Eqs.(2)-(4) are also established, based on the daily mean wind speed data at gauge height (for the CSPG, it is 0.7m.) and air temperature data.

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

Comments from Referees:

Page 2210, equation 8: What results did you get for z0 – do they seem reasonable? Was there a lot of scatter? How much did the wind speeds change with this correction? I also suggest to apply or develop any adjustment function with the gauge height wind speed. You can compare the results and evaluate if the wind speed adjustment is introducing additional uncertainty.

Author's response: In the revised version, two kinds of equations are established as described above. The uncertainties and Z_0 value are analyzed in the section 4.3 and in Fig.10.

Author's changes in manuscript: See relevant revision above.

Comments from Referees:

Page 2210, equations 10 and 11: Did you check for temperature dependency? That is a variable in the existing adjustment functions. You need to comment, why you don't use it. And as commented under general comments: it is good practice to compare the new and old adjustment functions in a quantitative way. Use calculated RMSE or other statistics to quantify the differences when applying the different set of equations.

Author's response: As answered above, two kinds of equations are given in the new versions. The F-test are used to test its statistics.

Author's changes in manuscript: See relevant revision above.

Comments from Referees: Page 2210, line 16 and lines 19/20: In all three figures, only ONE value is shown with a wind speed higher than 4 m/s. In panels b and c, this value is determining the slope of the regression line. That is too little evidence to conclude any existing or non-existing wind dependency.

Author's response: New figures and equations have been given in the revised versions.

Author's changes in manuscript: For the mixed precipitation, some equations are shown in Table 4 and are listed as Eqs. (12)-(17). The Fig.6 is shown as:

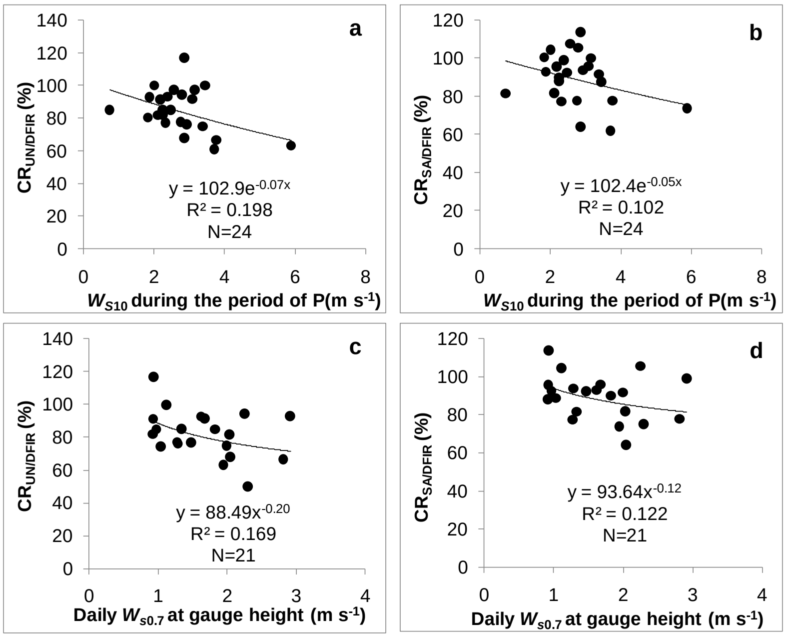


Figure 6. Catch ratios (CRs) vs. wind speed for the mixed precipitation event (**a** and **b**) and the daily mixed precipitation (**c** and **d**) greater than 1.0mm.

Comments from Referees: Page 2211, line 11. The catch ratio plots for Alter wind shield and Pit gauge and the calculated regression lines are rather similar, most likely due to the rather low wind speed interval shown. It remains unclear why the pit gauge can act as a reference, but the single Alter cannot.

Author's response: This part has been revised after data updated.

Author's changes in manuscript: The new version:

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 $\alpha<0.001$. The Eq.(18) is similar with the Eq.(5) suggested by Yang et al. (1991). For the $CSPG_{SA}$, the power law expression Eq.(19) passes the F-test when $\alpha<0.05$ (Table 4).

Fig.7 about here

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

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

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

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

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

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.

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

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

Comments from Referees: Page 2212, lines 10-16: The cited results from Ren and Li (2007) are covering a large range, while your results are single numbers, which happen to be somewhere in the presented intervals from the other study. It would be more reasonable to pick sites which have a similar climate to what you experienced during your measurements and compare only those results to your findings.

Author's response: Ok. It has been revised according to the new reference.

Author's changes in manuscript: The new version:

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

Comments from Referees:

Page 2212, line 20: There is no evidence in your paper, that the pit gauge was superior to the DFIR in your study. There may be indications that it performed similar, but even that would need a more thorough analysis.

Author's response: Ok. It has been revised.

Author's changes in manuscript: 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 difference of total snowfall (43 events) between the $CSPG_{PIT}$ and the $CSPG_{DFIR}$ is only about 3.4 mm from September 2012 to April 2015 at the Hulu watershed site. Thus the $CSPG_{PIT}$ could serve as a reference for liquid and solid precipitation in the environment similar to the Hulu watershed site.

Comments from Referees: Table 1: Insufficient caption; explanations of elements are needed.

Author's response: It has been revised.

Author's changes in manuscript: See below.

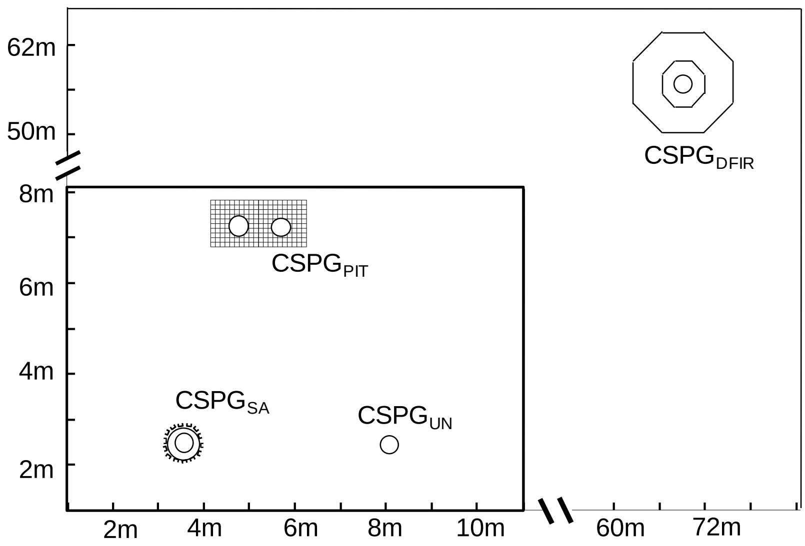
Table 1. Monthly climate values at the experimental site (2010-2012).

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

Comments from Referees: Figure 1: The layout in the upper right panel can hardly be realistic. The pictures indicate a rather short distance between the unshielded and single alter shield, far lower than the diameter of the DFIR. Please add distances in the layout and use a scaled illustration.

Author's response: Ok.

Author's changes in manuscript: See the new figure.



Comments from Referees:

Figures 2-9: Insufficient captions. At least, it needs to be stated that you are showing accumulation and catch ratios (don't use abbreviation here), respectively.

Author's response: Ok.

Author's changes in manuscript: The captions of Figures 2-7 are revised as (two figures are deleted):

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

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

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

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

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

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

Precipitation measurement intercomparison in the Qilian Mountains, Northeastern Tibetan Plateau

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Abstract: Systematic errors in gauge-measured precipitation are well-known, but the wind-induced error of Chinese standard precipitation gauge (CSPG) has not been well tested. ~~no reports have come from the Tibet Plateau.~~ An intercomparison experiment was carried out from September 2010 to ~~September~~ April ~~2014~~ 2015 in the Hulu watershed, northeastern Tibet Plateau. Precipitation gauges included ~~a~~ (1) an unshielded ~~Chinese standard precipitation gauge~~CSPG (CSPG$_{UN}$), (2) ~~a CSPG with~~single Alter ~~shelter~~shield around a CSPG (~~Alter~~CSPG$_{SA}$), (3) a CSPG in a Pit ~~type gauge with the CSPG~~ (~~Pit~~CSPG$_{PIT}$) and (4) a Double-Fence International Reference ~~with Tretyakov shelter and~~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. ~~t~~The ~~Pit~~ CSPG$_{PIT}$ and the CSPG$_{DFIR}$ caught more 3.6% and 2.5% rainfall, 7.3% and 6.0% more mixed precipitation, 4.4% and 8.5% more snowfall, and 3.9% and 3.2% more total precipitation than the CSPG$_{SA}$, respectively. ~~gauge~~Whereas the CSPG$_{DFIR}$ –caught 1.0% ~~more~~ less rainfall, 1.2% ~~more~~ less mixed precipitation, ~~4~~3.9% ~~less~~ more snowfall and 0.~~8~~6% ~~less~~more total precipitation ~~(all types)~~ than the CSPG$_{PIT}$~~DFIR from September 2012 to September 2014.~~, respectively.~~The Pit caught 4% more rainfall, 21% more snow and 16% more mixed precipitation than the CSPG. The DFIR caught 3% more rainfall, 27% more snowfall, and 13% more mixed precipitation than the CSPG, respectively.~~ From most to least~~or~~ rain and mixed precipitation, the ~~catch ratios (CRs) for the gauges~~measurements are ranked as follows: ~~CR$_{Pit}$~~ CSPG$_{PIT}$ > ~~CR$_{DFIR}$~~ CSPG$_{DFIR}$ > ~~CR$_{Alter}$~~ CSPG$_{SA}$ > ~~CR$_{CSPG}$~~CSPG$_{UN}$. For the snowfall, ~~the CRs are ranked as~~it follows as: ~~CR$_{DFIR}$~~ CSPG$_{DFIR}$ > ~~CR$_{Pit}$~~ CSPG$_{PIT}$ > ~~CR$_{Alter}$~~ CSPG$_{SA}$ > ~~CR$_{CSPG}$~~CSPG$_{UN}$.~~,~~ The CSPG$_{DFIR}$ is used as reference to calculate the catch ratios (CRs) of the CSPG$_{UN}$, CSPG$_{SA}$ and CSPG$_{PIT}$. ~~Catch ratio~~CR vs. 10m wind speed indicates that

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with increasing wind speed from 0 to 4.58.0m/s, the rainfall CR_{CSPG} $CR_{UN/DFIR}$ or CR_{Alter} $CR_{SA/DFIR}$ decreased slightly. For the mixed precipitation, the ratios of DFIR/Alter or DFIR/Pit vs. wind speed show that wind speed has no significant effect on catch $CR_{UN/DFIR}$ or $CR_{SA/DFIR}$ ratio below 3.5m/s. For the snowfall, the ratio of $CSPGCR_{UN/DFIR}$ or – $AlterCR_{SA/DFIR}$ vs. wind speed shows that catch ratioCR decreases with increasing wind speed. The calibrationadjustment equations for three different precipitation types for the $CSPG_{UN}$ and $CSPG_{SA}$and Alter – were established with 10m wind speeds based on the CR vs. wind speed analysis and World Meteorological Organization (WMO) recommonded procedure. They would help to improve the current bias error-adjusted method and precipitation accuracy in China. Results indicate that combined use of the $CSPG_{DFIR}$ and the $CSPGPi_{PIT}$ as reference gauges for snowfall and rainfall, respectively, could enhance precipitation observation precision. Applicable regions for the Pit gauge$CSPG_{PIT}$ or the $CSPG_{DFIR}$ as representative gauges for all precipitation types are present in China.

Keywords: Precipitation, Pit gauge, 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 errorsIt would affect the available water evaluation in a large number of economic and environmental applications (Tian et al., 2007; Ye et al., 2012).

The first World Meteorological Organization (WMO) precipitation measurement intercomparison started in 1955 (Rodda, 1973). Its reference is a Mk2 gauge elevated 1 m above the ground and equipped with the Alter wind shield. But this reference does not show the correct amount of precipitation. This could be why the first international intercomparison failed (Struzer, 1971). Rodda (1967) compared the catch of an 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. The This pitgauge in a –pit gauge caught 6% more precipitation than the normally exposed gauge. In the second WMO precipitation measurement intercomparison (Rain, 1972–1976), the pit gauge with anti-splash grid was designated the reference standard shield for rain gauges (Sevruk and Hamon,1984) (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 –shielded a Tretyakov shield Tretyakov gauge was

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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 calibrationadjustment procedure (Lanza et al., 2005; Sevruk et al., 2009). Because automation of precipitation measurements are widespread Considering the automation of precipitation measurements, the WMO Commission for Instruments and Methods of Observation (CIMO) organized the WMO Solid Precipitation Intercomparison Experiment (WMO-SPICE; YangWolff et al., 2014) to define and validate automatic field instruments as references for gauge intercomparison, and to assess automatic systems and the operational networks for precipitation observations. The WMO-SPICE project still selected DFIR shield as part of the reference configurations. The WMO-SPICE project selected double fence gauges as the reference.

Although adjustment procedures and reference measurements were developed in several WMO international precipitation measurement intercomparisons (Goodison et al., 1998; Yang, 2014), these have not been tested in the Tibetan Plateau. Because precipitation is concentrated in warm season on the Tibetan Plateau and is infrequent in winter, additional attention must be paid to systematic errors of gauge-measured precipitation. The DFIR has been operated as a part of reference configurations at 25 stations in 13 countries around the world (Golubev, 1985; Sevruk et al., 2009), but deviations from the DFIR measurements vary by gauge type and precipitation type (Goodison et al., 1998). In China, the DFIR was compared with 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°74′ N, 8786°49′ E, 3472 3720 m), during the third WMO precipitation measurement intercomparison experiment from 1987 to 1992, (Yang, 1988; Yang et al., 1991). The wetting, evaporation losses and trace precipitation of CSPG were well quantified based on the huge observation data. Because there are notwithout wind data at the intercomparison site (Yang et al., 1991; Goodison et al., 1998). Consequently, ,for the wind-induced undercatch, the derived CSPG catch ratio equations were based on the 10 m height wind speed at the open Daxigou Meteorological Station (43.06°, 86.5°E, 3540 m; Yang, 1988; Yang et al., 1991). Wind speedsThe distance is about 1.7 km atbetween the Daxigou open site and the Tianshan valley site thus their wind speeds are different, inducing uncertainty in the catch ratio equations established by Yang et al. (1991) for the CSPG. During the period from 1992 to 1998, Ren and Li (2007) had conducted an intercomparison experiment at 30 sites (altitude varies from about 4.8 m to 3837 m) over China, and they used the pit as reference shield. A total of 29,000 precipitation events had been observed. However, the DFIR was not used as reference configurations, and there were only 3 stations located in the West Cold Regions of China (Chen et al., 2006) where the solid precipitation often occurred. Blowing snow and thick snow cover have traditionally limited the pit's use as a reference shield for snowfall and mixed precipitation (snow with rain, rain with snow). Ye et al. (2004, 2007) developed a bias-error adjusting method based on the observed data from 1987 to 1992 at the Tianshan valley site, and they found a new precipitation trend according to the adjusted precipitation data over the past 50 years in China (Ding et al., 2007). The new adjusted precipitation would change the knowledge on water balance in many basins in China (Tian et al., 2007; Ye et al., 2012). ~~As the Tibetan Plateau is an ecologically fragile region and the source of several large rivers in China and neighborhood countries, accurate precipitation data is urgently needed.~~ Although adjustment procedures and reference measurements were developed in several WMO international precipitation measurement intercomparisons (Goodison et al., 1998; Sevruk et al., 2009; Yang, 2014), and several bias-error adjusting methods had been put forward for the CSPG (Ye et al., 2004, 2007), the wind-induced error of CSPG ~~these have~~ad not been well tested ~~in~~ especially in the cold and high regions such as the Tibetan Plateau, China.~~. Because precipitation is concentrated in warm season on the Tibetan Plateau and is infrequent in winter~~ In these cold regions, solid precipitation often occurs ~~,~~ and additional attention must be paid to ~~systematic~~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. ~~Considering that no other intercomparison experiments have been conducted or reported from the Tibetan Plateau and around regions (Chen et al., 2006), h~~Therefore, we present~~ere it presents~~ a nearly ~~four~~five-years ~~gauge i~~intercomparison experiment in the Qilian mountains ~~at~~ at the northeastern Tibet Plateau, China, to establish ~~calibration~~adjustment equations for the widely used unshielded and single Alter shield (Struzer, 1971) around CSPGs (CSPG$_{UN}$ and CSPG$_{SA}$) ~~and Alter gauges~~.

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The CSPG is the standard manual precipitation ~~observation~~ gauge used by the China Meteorological Administration (CMA) at more than 700 stations since the 1950s. These precipitation data sets have been used widely ~~without calibration~~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 ~~an Alter shied~~SA shield (~~Alter~~CSPG$_{SA}$) was selected as another intercomparison gauge. The ~~Pit and the~~ CSPG$_{DFIR}$ ~~were~~ was selected as the reference ~~gauges for rainfall and snowfall, respectively~~ for all precipitation types. The

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intercomparison experiments tested and assessed existing bias ~~correction~~ adjustment procedures for the $CSPG_{UN}$ and the $CSPG_{SA}$~~Alter~~. ~~Blowing snow and thick snow cover have traditionally limited the Pit's use as a reference gauge for snowfall and mixed precipitation. Snowfall is infrequent in China and snow depths rarely over 10cm in most part of China, so the Pit gauge has strong potential as a reference gauge for mixed precipitation and snowfall. The Pit and the DFIR catch ratios for snowfall and mixed precipitation are also compared. The CMA stations observe wind speeds at 10m height, so the CSPG and Alter calibration~~adjustment ~~equations are established with 10m height wind speeds rather than gauge height wind speeds.~~

2 Data and Methods

2.1 Intercomparison experiments and relevant data

Precipitation intercomparison experiments (Fig.1, Table 1) were conducted at a grassland site in the Hulu watershed in the Qilian mountains, on the northeastern edge of Tibet Plateau, China (99°52.9′, 38°16.1′, 2980m~~),~~). ~~where a~~A meteorological cryosphere-hydrology observation system (Chen et al., 2014) has been established since 2008 in the Hulu watershed. Annual precipitation is about 447.2 mm during 2010-2012 and precipitation occurs most frequently during the warm season from May to September at this site. ~~Annual precipitation is about 447 mm and concentrated in the warm season from May to September.~~ The annual temperature is approximately 0.4 °C, with a July mean (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

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measurements, 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 methods vary largely in spatial, and their reference precipitation phase data are still from the CMA's stations.

Relevant variables such as air temperature (maximum~~,~~ and –minimum~~ and mean~~; T_{max}~~, –~~ and T_{min}~~ and T_a~~) 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 ~~etc.~~ (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 ~~shown~~ summarized in Table 1.

Fig.1 about here

Table 1 and Table 2 about here

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

~~**Table 2 about here**~~

2.2 Adjustment methods

This field experiment focuses on two key aspects. One is comparisons among the $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$. Another purpose is to establish adjustment equations for $CSPG_{UN}$ and $CSPG_{SA}$ by using $CSPG_{DFIR}$ as reference. To ~~correct~~ adjust the gauge-measured precipitation, Sevruk and Hamon (1984) have given the general formula as:

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

Where P_c is the ~~corrected~~ 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

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DFIR-measured 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 0.23mm for rainfall measurements, and 0.30mm for snow and 0.29 mm for mixed precipitation (Yang, 1988; Yang et al., 1991)., according to the measurements in the Tianshan valley site. Ren and Li (2007) reported a mean value as about 0.19 mm for total precipitation over eastern China. The CSPG design reduces P_e to a value less smaller than other losses in the warm, rainy season (Ye et al., 2004; Ren and Li, 2007). In winter, P_e is already small (0.10–0.20 mm/day) according to results in Finland (Aaltonen et al., 1993) and Mongolia (Zhang et al., 2004). To prevent evaporation loss in Chinese operational observations on some particular days, e.g., hot and dry days or days of snow, precipitation is measured as soon as the precipitation event stops (CMA, 2007a; Ren and Li, 2007). A precipitation event of less than 0.10mm is beyond the resolution of the China recorderCSPG and is recorded as a trace amount of precipitation (P_t). Ye et al. (2004) recommended assigning a value of 0.1 mm, regardless of the number of the trace observations per day.

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

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 ($CR=1/K=P_g/P_{DFIR}$, %) versus daily wind speed (W_s, m/ s^{-1}) at gauge heightgauge height, and daily maximum and minimum temperatures (T_{max}, T_{min}, °C) on a daily time step for various precipitation types (Yang et al., 1995; Goodison et al., 1998). These equations can be used over a great range of environmental conditions (Goodison et al., 1998). Therefore, in this paper, the catch ratio (CR, %) follows their definition by using $CSPG_{DFIR}$ as reference.

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

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

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

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

The CMA stations usually observe wind speeds at 10m height, so Yang et al. (1991) and Ye et al. (2007) have given Eqs.(5)-~Eqs.(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

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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_0~~ T_{mean} is the daily mean air temperature (°C).

~~In this field experiment, two aspects are focused. One is based on rainfall observations comparisons among the CSPG, Alter and Pit gauges to establish calibration equations for the CSPG and the Alter with 10m height wind speeds. Another purpose is~~ In this paper, two types of equations are established. One is for easy application by using 10m-height wind speed during the period of precipitation in China. They are similar to and revisions of the Eqs.(5)-(7). Another type is similar to Eqs.(2)-(4), which use daily mean wind speed at gauge height. For CSPG, the gauge height is 70cm (Table 2).~~based on snow and mixed precipitation observation comparisons among the CSPG, Alter, Pit, and DFIR, to establish calibration~~adjustment ~~equations for snow and mixed precipitation with 10m height wind speeds.~~

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

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

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

Where Z is 0.7 m or 10 m.

3 Results

From September 2010 to ~~September~~ April ~~2014~~2015, a total of ~~578~~ 608 ~~observations~~ precipitation events were recorded at the intercomparison site for $CSPG_{UN}$, $CSPG_{SA}$ ~~Alter~~ and $CSPG_{PIT}$ ~~Pit~~, respectively (Table 3). Snow ~~happen~~occurred ~~67~~ 84 times, mixed precipitation ~~only happen~~occurred ~~32~~ 44 times, and rain ~~happen~~occurred ~~479~~ 480 times during this period. From September 2012 to ~~September 2014~~April 2015, a subset of ~~253~~ 283 ~~observations~~ precipitation events were recorded for the $CSPG_{UN}$, $CSPG_{SA}$ ~~Alter~~, $CSPG_{PIT}$ ~~Pit~~, and $CSPG_{DFIR}$ gauges respectively (Table 3). During this period, snow occurred 43 times, mixed precipitation occurred 29 times, and rainfall occurred 211times.

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Table 3 about here

3.1 Precipitation gauge intercomparison for rainfall

Good linear correlations are found among the four CSPG installments (Fig.2). From September 2010 to April 2015, ~~The Pit was selected as the reference gauge, and 479 rainfall events recorded by three different gauges from September 2010 to September 2014 were used in the intercomparsion studies (Table 3). The~~ the ~~Pit~~ $CSPG_{PIT}$ caught 4.7% and 3.4% more rainfall than the $CSPG_{UN}$~~,~~ and the ~~3.4% more than the Alter~~$CSPG_{SA}$ respectively (($CSPG_{PIT}$-$CSPG_{UN}$)/$CSPG_{UN}$*100; similarly hereinafter). The $CSPG_{SA}$ caught 1.3% more rainfall than the $CSPG_{UN}$ (Table 3).

~~For rainfall events f~~During the period from September 2012 to ~~September 2014~~April 2015, the $CSPG_{SA}$, $CSPG_{PIT}$, $CSPG_{DIFR}$ caught 0.9%, 4.5% and 3.4% more rainfall than the $CSPG_{UN}$, respectively. The $CSPG_{PIT}$ and the $CSPG_{DFIR}$ caught more 3.6% and 2.5% rainfall than the $CSPG_{SA}$, respectively. Whereas the $CSPG_{DFIR}$ caught 1.0% less rainfall than the $CSPG_{PIT}$ (Table 3, Fig.2). ~~DFIR was selected as the reference gauge. The DFIR caught 3.4% more rainfall than the CSPG, 2.5% more than the Alter, and 1.0% less than the Pit (Table 3).~~ Comparative studies indicate that ~~the Pit gauge CR~~$CSPG_{PIT}$ ~~is superior to that of the~~catches more rainfall and total *P* than the $CSPG_{DFIR}$ or the other gauges at the experiment site (Table 3, Fig.2).

Fig.2 about here

3.2 Precipitation gauge intercomparison for mixed precipitation

From September 2010 to April 2015, a total of 44 mixed precipitation events were observed. The $CSPG_{PIT}$ caught 12.1% and 5.6% more mixed *P* than the $CSPG_{UN}$ and the $CSPG_{SA}$, respectively. The $CSPG_{SA}$ caught 6.1% more mixed *P* than the $CSPG_{UN}$ (Table 3). From September 2012 to April 2015, the $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DIFR}$ caught 7.7%, 15.6% and 14.2% more mixed *P* than the $CSPG_{UN}$, respectively. The $CSPG_{PIT}$ and the $CSPG_{DFIR}$ caught more 7.3% and 6.0% mixed *P* than the $CSPG_{SA}$, respectively. Whereas the $CSPG_{DFIR}$ caught 1.2% less mixed *P* than the $CSPG_{PIT}$ (Table 3).

Good linear correlations are observed among the gauges (Fig.3). The $CSPG_{PIT}$ caught 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)~~with 98% confidence~~. Thus the $CSPG_{PIT}$~~Pit gauge~~ instead of the $CSPG_{DFIR}$ could be

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selected as the reference gauge of mixed precipitation to calculate CRs for the $CSPG_{UN}$ and the $CSPG_{SA}$ at the experimental site Alter.

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

Fig.3 about here

Fig.4 about here

3.3 Precipitation gauge intercomparison for snowfall

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

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

Good linear correlations are also observed between the $CSPG_{DFIR}$ and each of the other three gauges (Fig.4). From Fig. 4f, there is a linear correlation existed between the $CSPG_{PIT}$ and the $CSPG_{DFIR}$ ($CSPG_{DFIR}$=1.029$CSPG_{PIT}$, R^2=0.994). Although the $CSPG_{DFIR}$ caught 3.9% more snowfall than the $CSPG_{PIT}$

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(Table 3), the total difference of 43-time snowfall between the $CSPG_{DFIR}$ and the $CSPG_{PIT}$ was only about 3.4 mm (Table 3). This suggests that~~means~~ the $CSPG_{PIT}$~~Pit gauge~~ could be used as the reference gauge for snow precipitation events at the experiment site.

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

Fig.~~5~~ 4 about here

~~**Fig.6 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 10m height, so the $CSPG_{UN}$ and the $CSPG_{SA}$ adjustment equations for single precipitation event are established with 10m height wind speeds during the period of precipitation. On daily scale, the adjustment equations similar to Eqs.(2)-(4) are also established, based on the daily mean wind speed data at gauge height (for the CSPG, it is 0.7m.) and air temperature data.

~~Here the relationships of rain, mixed precipitation, and snow catch ratios to wind speed during the precipitation periods are analyzed.~~ To minimize ratio scatter of among different gauges, precipitation events greater than 3.0 mm are normally selected in the ratio vs. wind analysis (Yang et al. 1995; Yang et al., 2014). In

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the Hulu watershed, most snowfall and mixed precipitation events are less than 3.0 mm. For this reason, single or daily snowfall and mixed precipitation greater than 1.0 mm was chosen to use~~d~~ here.~~in this study for catch ratio vs. wind studies.~~ Whereas for the rainfall, precipitation greater than 3.0 mm was selected. The numbers of the chosen precipitation events are shown in Table 4. The catch ratio vs. wind speed relations of different precipitation types are summarized in Table 4 too. As shown in Table 4, all the $CR_{PIT/DFIR}$ vs. $W_{s0.7}$ or W_{s10} relations do not pass the F-test when α=0.10. Therefore, only $CR_{UN/DFIR}$ and $CR_{SA/DFIR}$ vs. wind speed relations are discussed in the following text.~~W_s at 10m height was calculated using half-hourly wind speed data at 1.5m and 2.5m heights, according to the Monin-Obukhov theory and the gradient method (Bagnold,1941; Dyer and Bradley, 1982):~~

Table 4 about here

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

~~$$W_{s0.7} = k_{0.7}W_{s1.5},\quad k_{0.7} = \frac{\ln(0.7/z_0)}{\ln(1.5/z_0)} \qquad (9)$$~~

3.4.1 Rainfall catch ratio vs. wind speed

~~Selecting the Pit gauge as the reference,~~ Fig.~~7~~ 5 presents scatter plots of the $CR_{UN/DFIR}$ or $CR_{SA/DFIR}$~~CRs of CSPG/Pit and Alter/Pit~~ vs. wind speed. The CRs vary from ~~0.8~~80% to ~~1.1~~110%. With increasing wind speed, the CRs decreased slightly. The following two equations (10) and (11) could be used to ~~calibrate~~ adjust the rainfall event data ~~for~~ from the $CSPG_{UN}$ and $CSPG_{SA}$, respectively. They both pass the F-test when α<0.1 (Table 4).~~gauge or the Alter gauge.~~

~~$$CR_{CSPG} = -0.01*W_s + 0.989 \qquad (10)$$~~

~~$$CR_{Alter} = -0.01*W_s + 0.998 \qquad (11)$$~~

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

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

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

Fig.~~7~~ 5 about here

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

3.4.2 Mixed precipitation catch ratio vs. wind speed

Fig.5c shows that a good liner relationship existed between the Pit and the DFIR for mixed precipitation measurement. Fig.8a shows that the Pit/DFIR CR is approximately 1, and wind speed has little effect on the Pit gauge for mixed precipitation. Thus the Pit gauge was selected as the reference to establish a regression equation between the CSPG/Pit CR and wind speed. For the mixed precipitation events, the $CR_{UN/DFIR,Mixed}$ and $CR_{SA/DFIR,Mixed}$ vs. W_{s10} relations are exponential (Table 4, Fig.6). The CRs vary largely from about 60% to 120%. For the $CSPG_{UN}$, the exponential relationship Eq. (12) passes the F-test when α<0.10, whereas for the $CSPG_{SA}$, the Eq.(13) doesn't pass and with an α value of about 0.16 (Table 4). Figs.8b and 8c show that the CSPG/Pit CR and the Alter/Pit CR decreased with increasing wind speed. Equations (12) and (13) were established to calibrate the CSPG or Alter gauge mixed precipitation data.

$$CR_{CSPG} = -0.051 * W_s + 1 \quad (12)$$

$$CR_{Alter} = -0.030 * W_s + 1 \quad (13)$$

Where CR_{CSPG} is the CSPG catch ratio, CR_{Alter} is the Alter catch ratio, and W_s is the wind speed at 10m height.

Fig.8 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 α<0.10, whereas the Eq.(15) doesn't with an α value of about 0.12 (Table 4).

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

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

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.

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

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

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

3.4.3 Snowfall catch ratio vs. wind speed

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

Fig.7 about here

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

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

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 the $CSPG_{SA}$.

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

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

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.

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

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

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

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$$CR_{CSPG} = -0.081 * W_s + 1 \quad (14)$$

$$CR_{Alter} = -0.016 * W_s + 0.957 \quad (15)$$

~~Where CR_{CSPG} is the CSPG catch ratio, CR_{Alter} is the Alter catch ratio, and W_s is the wind speed at 10 m height.~~

~~**Fig.9 about here**~~

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 ~~DFIR/CSPG~~$CSPG_{DFIR}/CSPG_{UN}$ for snowfall and mixed precipitation were 1.222 and 1.160, respectively. In the Hulu watershed, the ratios of $CSPG_{DFIR}/CSPG_{UN}$~~DFIR/CSPG~~ for snowfall and mixed precipitation were 1.~~234~~ 165 (Fig.4c) and 1.~~069~~072 (Fig.3c), and the ratios of $CSPG_{PIT}/CSPG_{UN}$~~Pit/CSPG~~ for snowfall and mixed precipitation ~~is~~ were 1.~~199~~ 162 (Fig.4b) and 1.~~078~~082 (Fig.3b), respectively. Similar topographic features and shading induced lower wind speeds at both sites, which led to the similar catch ratios. For the Tianshan reference site, wind speed (W_{s10}) on rainfall or snowfall days never exceeds 6 m s^{-1}~~m/s~~ and 88% of the yearly total precipitation took place with wind speeds below 3 m s^{-1}~~m/s~~. For the Hulu watershed site, daily mean wind speeds on precipitation days ($W_{s0.7}$) never exceeded ~~4.5~~3.5 m s^{-1}~~m/s~~, and over ~~80~~98.9% of the precipitation events ~~happen~~occurred when daily mean wind speeds were below 3 m s^{-1}~~m/s~~. During the period of precipitation, the largest wind speed at 10m 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~~et al. (~~2007~~2003) reported, among 30 comparison stations in China, the $CSPG_{PIT}$~~Pit~~ caught 3.2% (1.1~7.9%) more rainfall and 11.0% (2.2~24.8%) more snowfall than the $CSPG_{UN}$~~CSPG~~. Large wind-induced differences are often ~~appeared~~ observed at the western mountainous stations and in the Northeastern China. At the Gangcha station (100°08′, 37°20′, 3015 m) which also lies in the Qilian Mountains with similar elevations with and about 200 km far from the Hulu watershed site, the $CSPG_{PIT}$ caught 7.9% more rainfall and 16.8% more snowfall than the $CSPG_{UN}$. In our study, the $CSPG_{PIT}$~~Pit gauge~~ got 4.7% more rainfall, ~~24.2~~21.0% more snowfall, and 1~~1.6~~2.1% more mixed precipitation than the $CSPG_{UN}$~~CSPG~~ from September 2010 to ~~September 2014~~April 2015 (Table 3). The outcome presented in this study is somewhat different from the~~similar with~~ Ren et al. (2003) ~~Ren and Li (2007)~~ presented due to the different wind regime.

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4.2 Possibility of the $CSPG_{PIT}$~~Pit gauge~~ 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~~The Pit gauge is the WMO reference standard for liquid precipitation measurements and the DFIR is the reference standard for solid precipitation measurements~~ (Sevruk et al., 2009). In this study, the $CSPG_{PIT}$~~Pit gauge~~ ~~performed superior~~measures more rainfall and mixed precipitation than the CSPGDFIR~~ for rainfall catch ratio and mixed precipitation catch ratios~~. For snowfall, the catch ratio for the $CSPG_{PIT}$~~Pit gauge~~ is 0.96, close to the CSPGDFIR catch ratio. The total 43-time snowfall difference between the $CSPG_{PIT}$ and the $CSPG_{DFIR}$ is only about 3.4mm from September 2012 to April 2015 at the Hulu watershed site. Thus the $CSPG_{PIT}$~~Pit gauge~~ could serve as a reference for liquid and solid precipitation in the environment similar to ~~in~~ the Hulu watershed site. Considering the $CSPG_{PIT}$~~Pit gauge~~'s greater simplicity and practicality, it could be more convenient for researchers and observers to use the $CSPG_{PIT}$~~Pit gauge~~ as the standard reference for snow and mixed precipitation in other locations. Precipitation collected by the $CSPG_{PIT}$~~Pit gauge~~ 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 20cm (Li, 1999), and average snow depths were less than 3cm (Li et al., 2008; Che et al., 2008). Fig.~~10~~ 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. ~~Scarcity of accumulated snow and little snowfall correlates to rare occurrence of blowing snow in most of China.~~ Ren and Li (2007) has reported, among the 29276 precipitation events, there are only 784 blowing or drifting snow events accounting to about 2.7% at the 30 stations over China. These blowing or drifting snow events mostly occur in the south-eastern Tibetan Plateau, northern Xinjiang province and north-eastern China (Ren et al., 2003). The applicable regions for the $CSPG_{PIT}$~~Pit~~ and the CSPGDFIR as reference gauges are shown in Fig.~~11~~ 9 based on CMA snowfall and snow depth data.

Fig.~~10~~ 8 about here

Fig.~~11~~ 9 about here

4.3 Uncertainties of the experiment

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

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

Fig. 10 about here

5 Conclusions

The precipitation intercomparsion experiment in the Hulu watershed indicates that the $CSPG_{PIT}$~~Pit gauge~~ catches more rainfall, mixed precipitation and total precipitation than the $CSPG_{DFIR}$. ~~The catch ratios for~~From most to the least rainfall and mixed precipitation, it can be ordered as follows: $CSPG_{PIT}$ > $CSPG_{DFIR}$ > $CSPG_{SA}$ > $CSPG_{UN}$~~CR_{Pit}> CR_{DFIR}>CR_{Alter}>CR_{CSPG}~~. While in the snowy season, it follows the rule that better wind-~~shelter~~shield catch with more snow, and ~~the catch ratios for snow~~ they can be ordered: $CSPG_{DFIR}$ > $CSPG_{PIT}$ > $CSPG_{SA}$ > $CSPG_{UN}$~~CR_{DFIR}>CR_{Pit}>CR_{Alter}>CR_{CSPG}~~. ~~The catch ratio of the Pit vs. DFIR reaches 1.01 for solid and liquid precipitation.~~ The wind-induced bias of $CSPG_{SA}$ and the $CSPG_{UN}$ are well tested, and the most adjustment equations could be used. They would help to improve the precipitation accuracy in China.

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

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References

Aaltonen, A., E., Elomaa, A., Tuominen, and P., Valkovuori: Measurement of precipitation, in: Proceedings of the Symposium on Precipitation and Evaporation, edited by: Sevruk, B. and Lapin, M., Slovak Hydrometeorlogical Institute and Swiss Federal Institute of Technology, Bratislava, Slovakia, 42–46, 1993.

Bagnold, R. A.: The Physics of Blown Sand and Desertdunes, Methuen , New York, 85-95, 1941.

Che, T., Li, X., Jin, R., Armstrong, R., and Zhang T.: Snow depth derived from passive microwave remote-sensing data in China, Ann. Glaciol., 49, 145-154, 2008.

Chen, R., , Kang E., Ji, X., Yang, J., and Yang, Y.: Cold regions in China, Cold Reg. Sci. Technol., 45, 95-102, doi:10.1016/j.coldregions.2006.03.001, 2006.

Chen, R., Song, Y., Kang, E., Han, C., Liu, J., Yang, Y., Qing,W., and Liu, Z.: A Cryosphere-Hydrology observation system in a small alpine watershed in the Qilian Mountains of China and its meteorological gradient, Arct. Antarct. Alp. Res., 46(2): 505-523. doi: http://dx.doi.org/10.1657/1938-4246-46.2.505, 2014a.

Chen, R., Liu, J., and Song, Y.: Precipitation type estimation and validation in China, J. Mt. Sci.,11(4): 917-925, doi: 10.1007/s11629-012-2625-x, 2014b.

China Meteorological Administration (CMA): Specifications for surface meteorological observation Part 8: Measurement of precipitation (QX/T 52-2007), China Meteorological Press, Beijing, 2007a.

China Meteorological Administration (CMA): Specifications for surface meteorological observation Part 4: Observation of weather phenomenon (QX/T 48-2007), China Meteorological Press, Beijing, 2007b.

Ding, Y., Yang, D., Ye, B., and Wang, N.: Effects of bias correction on precipitation trend over China, J. Geophys. Res., 112, D13116, doi:10.1029/2006JD007938, 2007.

Ding, B., Yang, K., Qin, J., Wang, L., Chen, Y., and He, X.: The dependence of precipitation types on surface elevation and meteorological conditions and its parameterization, J. Hydrol., 513, 154163, 2014.

Dyer, A. J., and Bradley, E. F.: An alternative analysis of flux-gradient relationships at the 1976 ITCE, Bound.-Lay. Meteorol., 22, 3–19, doi: 10.1007/BF00128053, 1982.

Golubev, V. S.: On the problem of actual precipitation measurements at the observations site, in: Proceeding of the International Workshop on the Correction of Precipitation Measurements WMO/TD 104, World Meteorological Organization, Geneva, Switzerland, 61–64, 1985.

~~Goodison, B. E., Sevruk, B., and Klemm, S.: WMO solid precipitation measurement intercomparison: Objectives, methodology and analysis, in: International Association of Hydrological Sciences, 1989: Atmospheric deposition. Proceedings, Baltimore Symposium, May 1989, IAHS Publication No. 179, IAHS Press, Wallingford, 57–64, 1989.~~

Goodison, B. E., Louie, B. P. Y. T., and Yang, D.: WMO solid precipitation measurement intercomparison: Final report, Instrum. and Obs. Methods Rep. 67/Tech. Doc. 872, World Meteorol. Organ., Geneva, Switzerland, 1998.

Lanza, L. G., Leroy, M., Alexandropoulos, C., Stagi, L., and Wauben, U.: WMO Laboratory Intercomparison of Rainfall Intensity Gauges – Final Report, IOM Report No. 84, WMO/TD No. 1304, WMO, Geneva, Switzerland, 2005.

Li, P.:. Variation of snow water resources in northwestern China, 1951-1997, Sci. China Ser. D, 42, 73-79, 1999.

Li, X., Cheng, G., Jin, H., Kang, E., Che, T., Jin, R., Wu, L., Nan, Z., Wang, J., and Shen, Y.: Cryospheric change in China, Global Planet. Change, 62, 210-218, doi:10.1016/j.gloplacha.2008.02.001, 2008.

Ma, Y., Zhang, Y., Yang, D., and Farhan, S.: Precipitation bias variability versus various gauges under different climatic conditions over the Third Pole Environment (TPE) region, Int. J. Climatol., doi: 10.1002/joc.4045, 2014.

Metcalfe, J. R., and Goodison, B. E.: Correction of Canadianwinter Precipitation Data. Preprints, in: Eighth Symp. on Meteorological Observations and Instrumentation, Anaheim, CA, Am. Meteorol. Soc., 338–343, 1993.

Ren, Z. and Li M.: Errors and Correction of Precipitation Measurements in China, Adv. Atmos. Sci., 24, 449–458, doi: 10.1007/s00376-007-0449-3, 2007.

Ren, Z., Wang, G., Zou, F., and Zhang, H.: The research of precipitation measurement errors in China, Acta Meteorol. Sin., 61, 621-627, 2003.

Rodda, J. C.: The rainfall measurement problem, in: Proceedings of IAHS, General Assembly, Bern 1967, Publication No. 78: 215-231, 1967.

Rodda, J. C.: Annotated Bibliography on Precipitation Measurement Instruments,WMO-No. 343, World Meteorol. Org, Geneva., Switzerland, 1973.

Sevruk, B., and Hamon,W. R: International Comparison of National Precipitation Gauges with a Reference Pit Gauge, Instruments and Observing Methods Rep., 17, 135, World Meteorol. Org., Geneva, 1984.

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

~~Strangeways, I. C.: CEN Standard for a Reference Raingauge Pit, Report of Working Group 5 to CEN/TC 318 – Hydrometry, British Standards Institution, London, UK, 1998.~~

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

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

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

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

Yang, D.: Research on analysis and correction of systematic errors in precipitation measurement in Urumqi River basin, Tianshan, PhD thesis, Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, Lanzhou, China, 169 pp., 1988.

Yang, D.: Double-Fence Intercomparison Reference (DFIR) vs. Bush Gauge for "true" snowfall measurement, J. Hydrol., 509, 94–100, doi:10.1016/j.jhydrol.2013.08.052, 2014.

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

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

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

Ye, B., Yang, D., Ding,Y., Han, T., and Koike,T.: A bias-corrected precipitation climatology for China, J. Hydrometeorol., 5, 1147–1160, doi: http://dx.doi.org/10.1175/JHM-366.1, 2004.

Ye, B., Yang, D., Ding, Y., and Han, T.: A bias-corrected precipitation Climatology for China. Acta Geogr. Sin., 62, 3-13, 2007.

Ye, B., Yang, D., and Ma, L.: Effect of precipitation bias correction onwater budget calculation in Upper YellowRiver, China, Environ. Res. Lett., 7, 025201, doi:10.1088/1748-9326/7/2/025201, 2012.

Zhang, Y., Ohata, T., Yang, D., and Davaa,G.: Bias correction of daily precipitation measurements for Mongolia, Hydrol. Process., 18, 2991–3005, doi: 10.1002/hyp.5745, 2004.

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

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

Gauge	Abbreviation	Size(φ stand for orifice diameter and h for observation height)	Start date	End date	Measure time
An unshielded China standard precipitation gauge (CMA, 2007a)	$CSPG_{UN}$	φ=20cm, h=70cm	Jun 2009	~~Sep~~Apr, ~~2014~~2015	20:00 and 08:00, LT
~~CSPG with~~Single Alter ~~shelter~~ shield (Struzer, 1971) around a CSPG	~~Alter~~$CSPG_{SA}$	φ=20cm, h=70cm	Jun 2009	~~Sep~~Apr, ~~2014~~2015	20:00 and 08:00, LT
A CSPG in a Pit ~~gauge~~ (Sevruk and Hamon, 1984) ~~with a CSPG~~	~~Pit~~$CSPG_{PIT}$	φ=20cm, h=0cm	Sep 2010	~~Sep~~Apr, ~~2014~~2015	20:00 and 08:00, LT
~~Double-Fence with CSPG~~DFIR shield (Goodison et al., 1998) around a CSPG	$CSPG_{DFIR}$	φ=20cm, h=3.0m	Sep 2012	~~Sep~~Apr, ~~2014~~2015	20:00 and 08:00, LT

Table 3. Summary of ~~daily~~ precipitation observations at the Hulu watershed intercomparison site, 2010-~~2014~~2015.

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

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

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

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

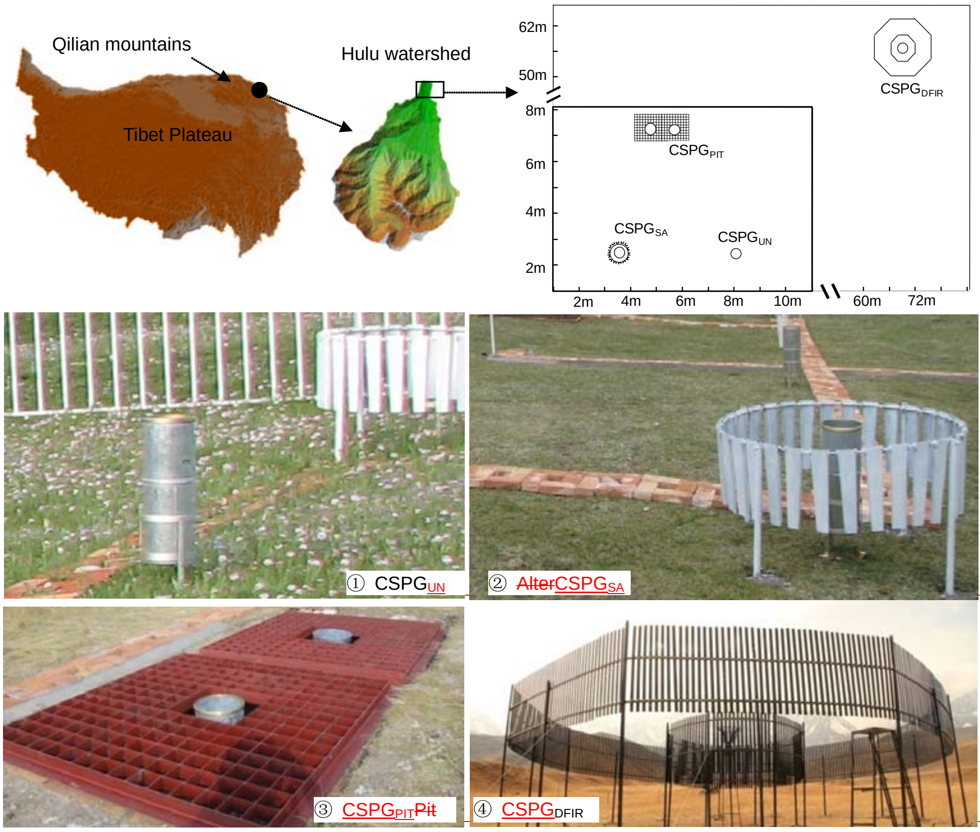

Figure 1. Precipitation gauge intercomparison experiment in the Qilian mountains, Tibetan Plateau.

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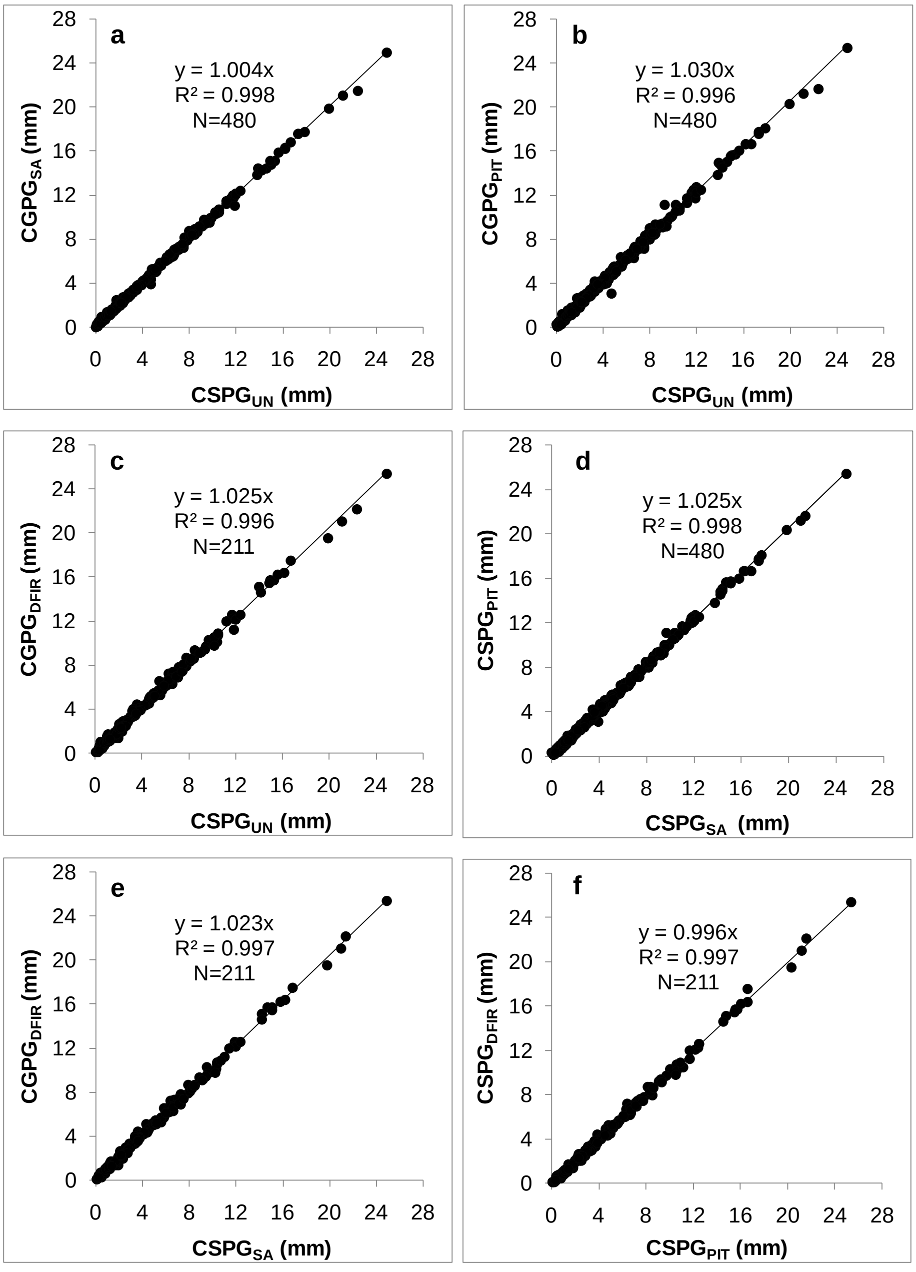


Figure 2. Intercomparison plots among $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ for the rainfall events from September 2010 (**a**, **b** and **d**) or September 2012 (**c**, **e** and **f**) to April 2015.

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

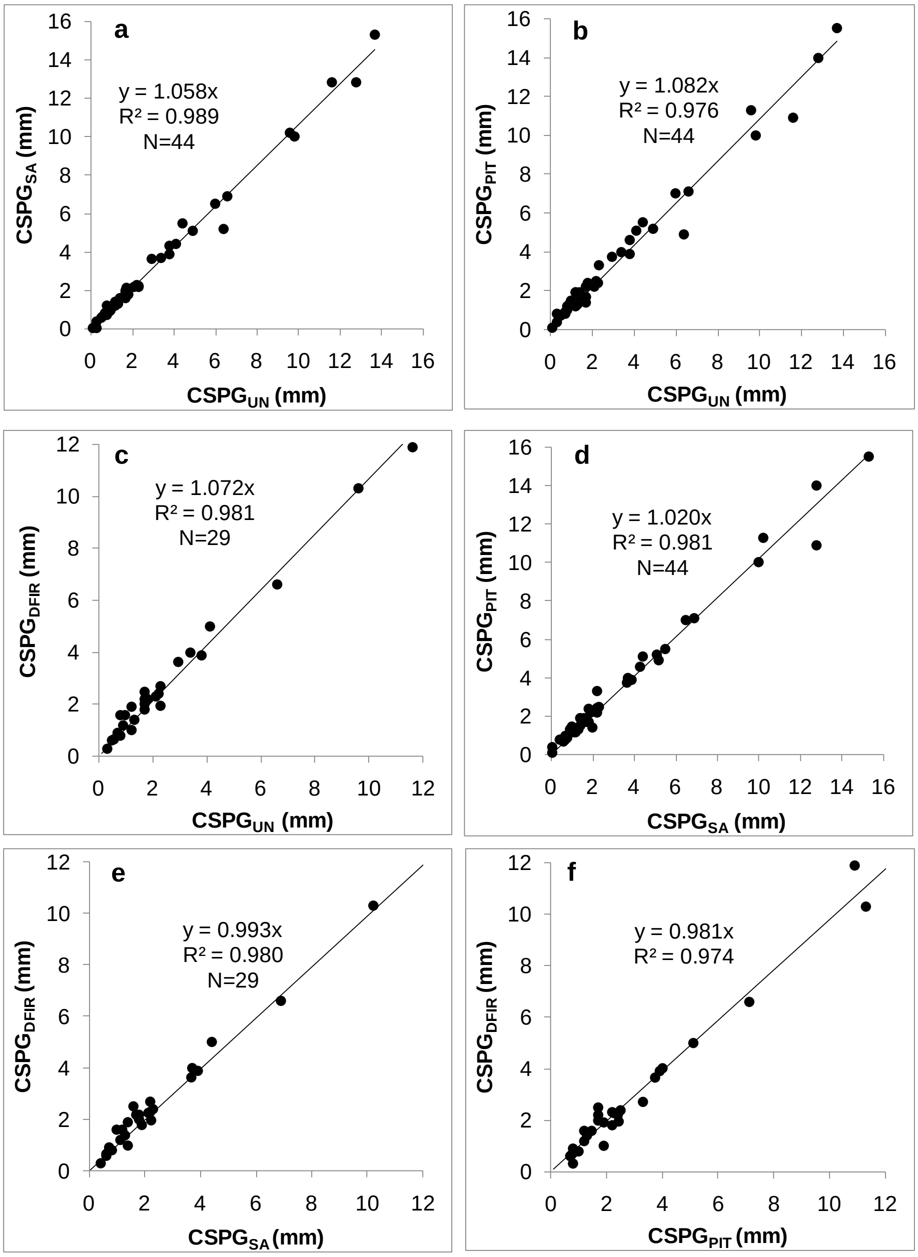
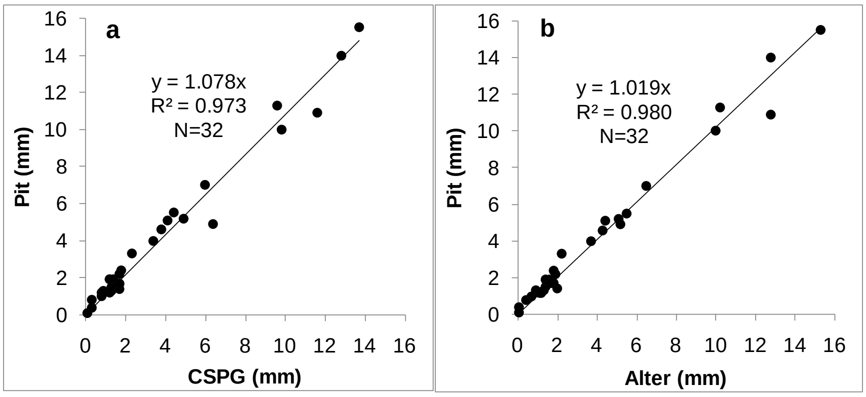


Figure 3. Intercomparison plots among $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ for the mixed precipitation events from September 2010 (**a**, **b** and **d**) or September 2012 (**c**, **e** and **f**) to April 2015.

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



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

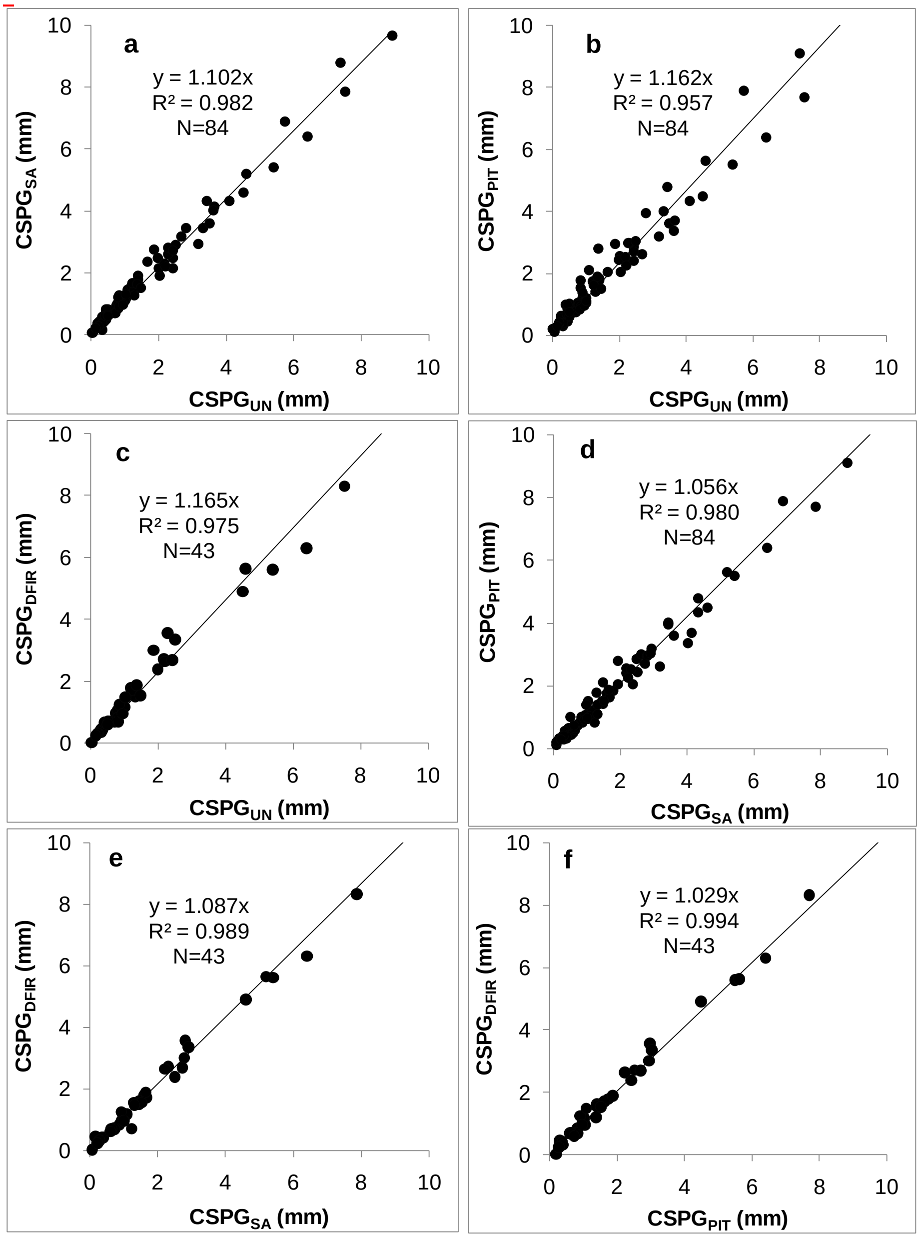


Figure ~~5~~4. Intercomparison plots among $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ for the snowfall events from September 2010 (**a**, **b** and **d**) or September 2012 (**c**, **e** and **f**) to April 2015.

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

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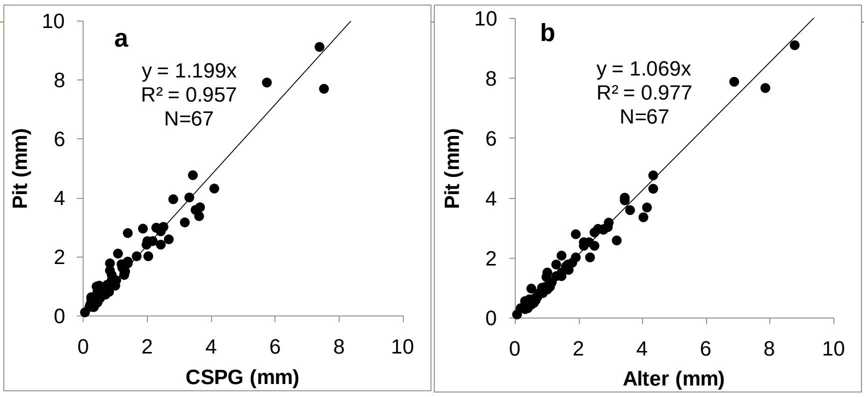

~~**Figure 6**. Scatter plots of snowfall for **(a)** the CSPG, and **(b)** the Alter vs. the Pit from September 2010 to September 2014.~~

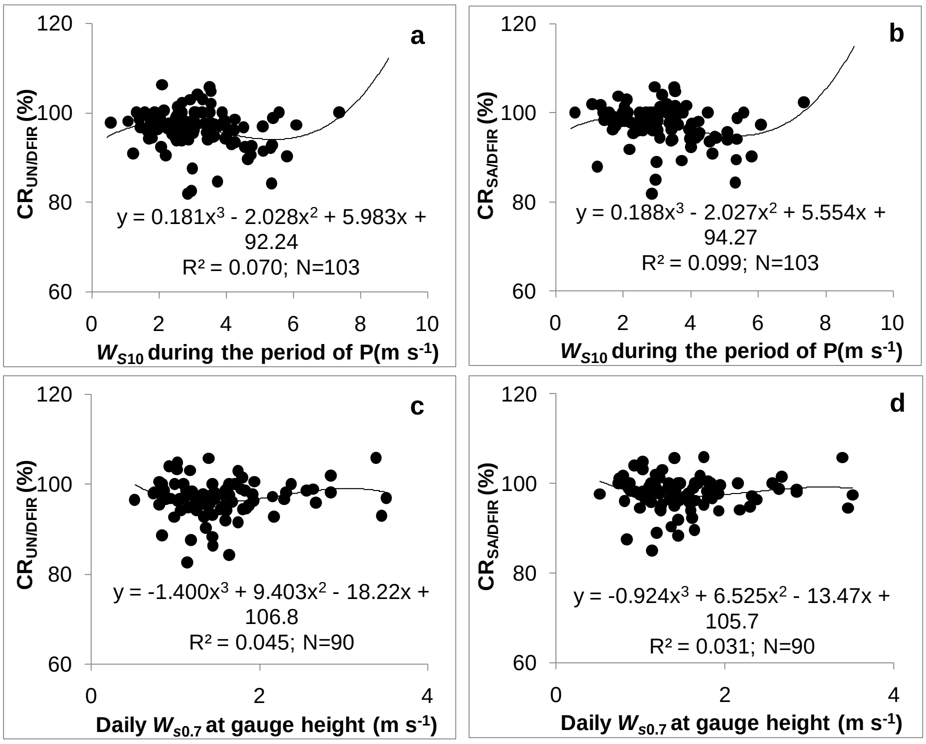

Figure 75. Catch ratios (CRs) vs. wind speed for the rainfall event (**a** and **b**) and the daily rainfall (**c** and **d**) greater than 3.0mm.

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

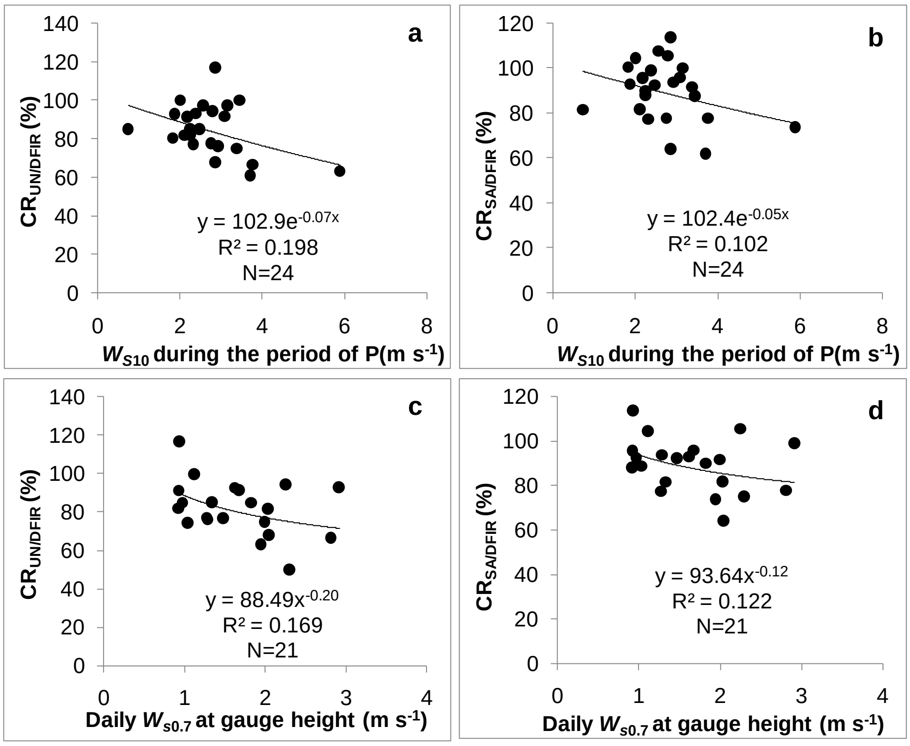

Figure ~~8~~6. Catch ratios (CRs) vs. wind speed for the mixed precipitation event (**a** and **b**) and the daily mixed precipitation (**c** and **d**) greater than 1.0mm. ~~CRs of (**a**) Pit/DFIR, (**b**) CSPG/Pit and (**c**) Alter/Pit vs. wind speed at 10m for Pit mixed precipitation >1.0mm.~~

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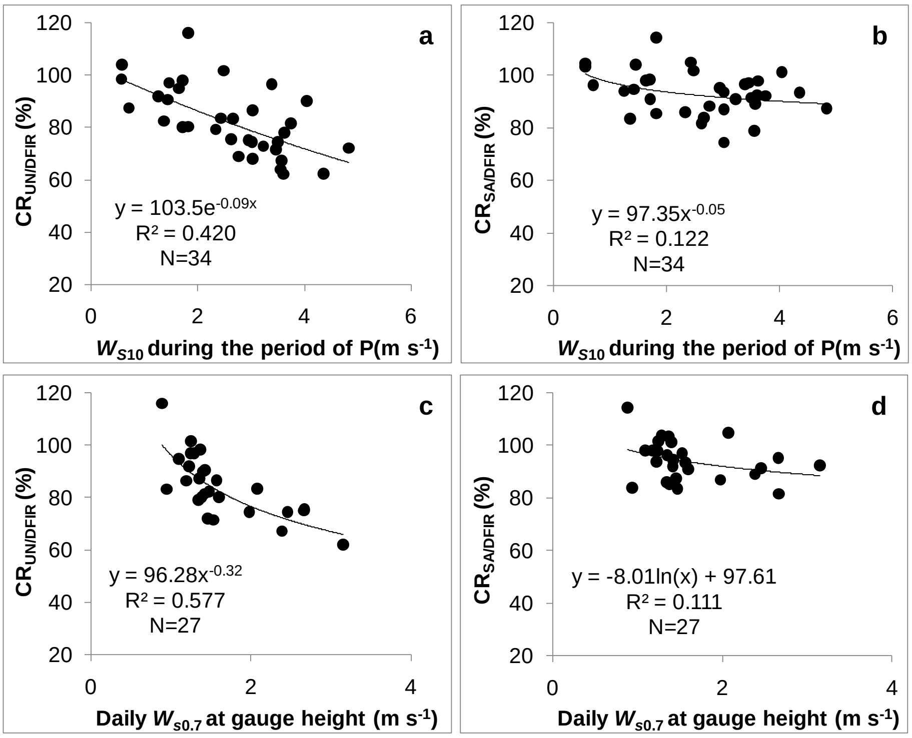

Figure 97. Catch ratios (CRs) vs. wind speed for the snowfall event (**a** and **b**) and the daily (**c** and **d**) snowfall greater than 1.0mm.CRs of (a) CSPG/DFIR, (b) Alter/DFIR and (c) Pit/DFIR vs. wind speed at 10m for DFIR snowfall >1.0mm.

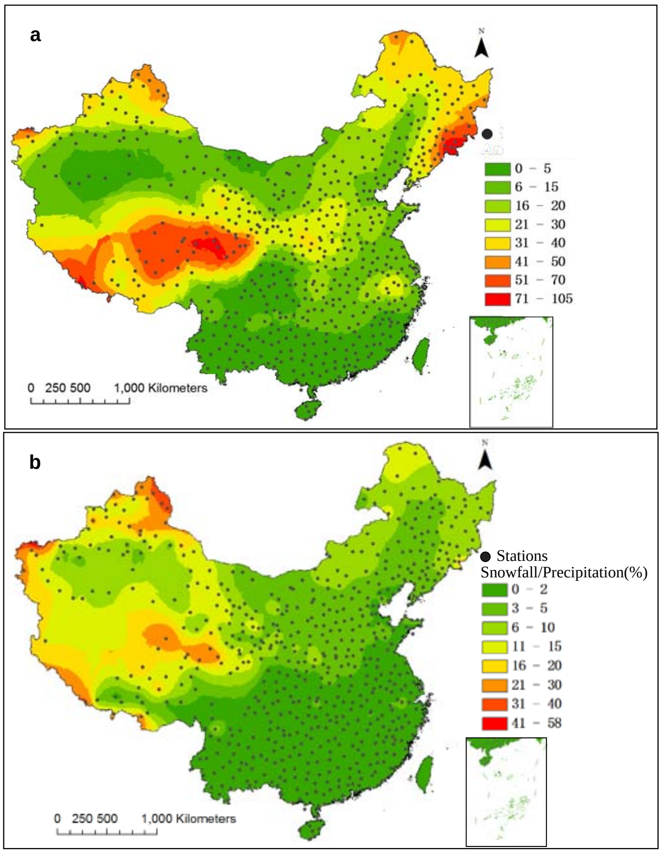

Figure ~~10~~8. (**a**) Annual snowfall (mm) and (**b**) snowfall proportion (annual snowfall/annual precipitation) in China.

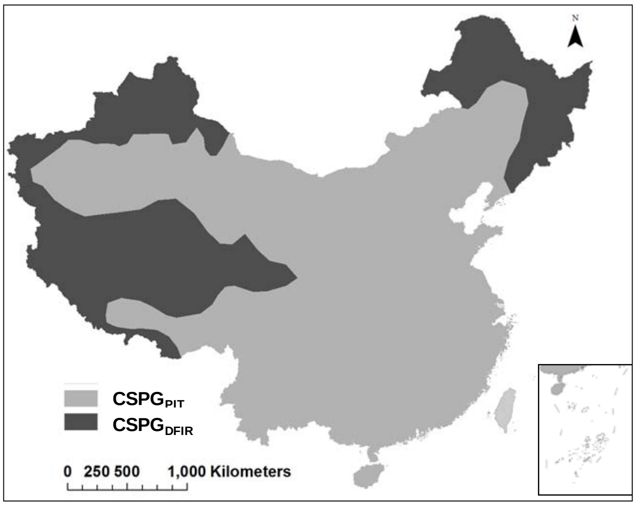

Figure ~~11~~9. Applicable regions for the ~~Pit~~ CSPG$_{PIT}$ and the CSPG$_{DFIR}$ as reference gauges in China.

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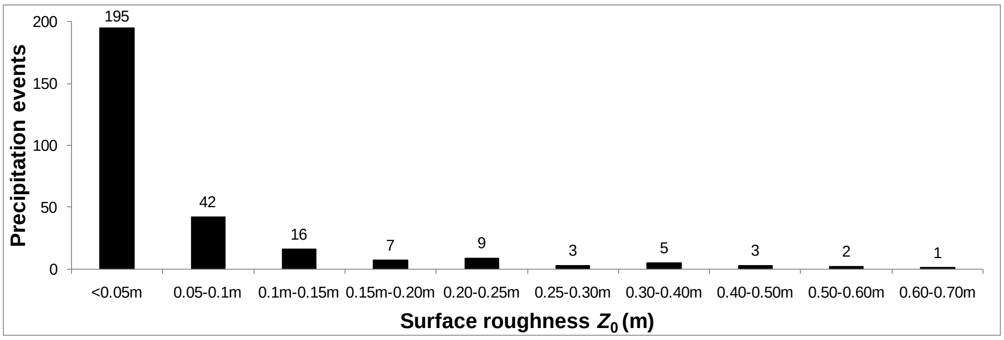

Figure 10. The surface roughness during the precipitation period from September 2012 to April 2015.