(1) Peer review comments on “Precipitation measurement intercomparison in the Qilian Mountains, Northeastern Tibetan Plateau” by R. Chen et al. (August 4, 2015)

Editor (August 4, 2015)

The manuscript has improved after the revision. There are however still issues here and there. There is a need to show more details in the fitting method, the use of F-test, and the derivation of the correction equations. A revision is necessary.

Authors' response: Thank you very much. These issues are put forward by the Referee #1. We have answered and revised them in the following parts.

Comments from Referees (August 4, 2015):

GENERAL COMMENTS

The manuscript improved a lot compared to the first version I reviewed. There are still a few unclear areas; I included my comments into the PDF document enclosed. I would like to see more details related to the fitting method and the use of F-test (chapter 2.2) and the derivation of the equations (chapter 3.3 and 3.4, Table 4). Also suggest adding a few lines comparing the maintenance requirements of the PIT and DFIR gauges (in chapter 4.2).

Authors' response: Thank you very much for your detailed and good advices. The unclear areas marked in the PDF file have been revised. The fitting method and the use of F-test are described in detail in the revised paper. A few lines are added to compare the maintenance requirements of the PIT and DFIR gauges.

Author's changes in manuscript:

1. **Reviewer #1 (August 4, 2015)** : "more details related to the fitting method and the use of F-test (chapter 2.2)"

New comments from the Editor (August 12, 2015): On August 12, Dr. Yang (editor) advised the fitting equations should consider the case when wind speed was 0 m/s, the catch ratio should be 100%. Thus, all the fitting equations and F-values should be revised. Therefore, we now use the SPSS 19.0 software.

First revision: The one independent variable equations were fitted directly by using Microsoft Excel. Whereas for the equations with more independent variables, the function NLINFIT in Matlab software was used. They are both based on the least square method in mathematics (Charnes et al., 1976). The significance of the equations were evaluated by using F-test method (Snedecor and Cochran, 1989). For the simultaneous equations, the F-value and its significant value (α) could be calculated by using function LINEST and FDIST in the Microsoft Excel, respectively. If the independent variable X presents in the forms like $X^{0.5}$, exp(0.5X) and 0.5ln(X) etc., its form should be revised to agree with the LINEST function. For example, the equation ' $Y=a*X_1^b+c*exp(d*X_2)+e$ ' should be revised as ' $Y=a*X_3+c*X_4+e$ ' before using LINEST to acquire its F-value.

Last Revision:

Page 7, Line 16-19 in the revised version: The equations were fitted using SPSS software version 19.0 (IBM, 2010) and Microsoft Excel 2007 based on the mathematical least squares method (Charnes et al., 1976). The significance of the equations was evaluated using the F-test method (Snedecor and Cochran, 1989). If the significance level (α) of the F-test is below 0.05, the fitted equation is significant. The lower the α value, the greater the significance.

Page 10, Line 21-26 in the revised version: As described in section 2.2, Eq.(10) was fitted using the NONLINEAR function in SPSS software (Analyze\Regression\Nonlinear). The F-value was then calculated using regression and the residual sum of squares from SPSS (Snedecor and Cochran, 1989). Based on the F-value and the degrees of freedom (Df), the significance level (α) was obtained using the FDIST function in Microsoft Excel. Other forms such as the exponential expression were treated in a similar way.

2. **Reviewer #1 (August 4, 2015)** :"more details related to the derivation of the equations (chapter 3.3 and 3.4, Table 4)."

First Revision. Some lines are added in Page 10 Line 17-20: As described in Chapter 2.2, to calculate the F-value of this kind of equation using LINEST function in Microsoft Excel, the W^3_{s10} and W^2_{s10} should be converted into new variables $X_1= W^3_{s10}$ and $X_2= W^2_{s10}$ firstly. Other forms such as the power law and exponential expressions are treated in a similar way.

Page 10, Line 21-26 in the revised version: As described in section 2.2, Eq.(10) was fitted using the NONLINEAR function in SPSS software (Analyze\Regression\Nonlinear). The F-value was then calculated using regression and the residual sum of squares from SPSS (Snedecor and Cochran, 1989). Based on the F-value and the degrees of freedom (Df), the significance level (α) was obtained using the FDIST function in Microsoft Excel. Other forms such as the exponential expression were treated in a similar way.

3. **Reviewer #1 (August 4, 2015)** "adding a few lines comparing the maintenance requirements of the PIT and DFIR gauges (in chapter 4.2)"

First revision:

Some lines are added in Page 12 Line 10: The pit shield is easy to transit, install, observe and maintain. It occupies only a small place and could be installed in the CMA'S standard meteorological fields, but the DFIR shield is large and should keep away from the other observations. In the mountains regions, the DFIR shield is difficult to move and install. In addition, the pit shield is only about 150 USD, 6000 USD cheaper than the DFIR shield in China. Therefore, it could be more convenient for researchers and observers to use the $CSPG_{PIT}$ as the standard reference for snow and mixed precipitation in other locations with very low winds.

Least revision after Editor's comments on August 12, 2015:

The paper should be "major revision" before the review starts. Editor Dr. Yang advise the coauthor Dr. E. Kang help to revise this paper. Dr. Kang has revised this paper thoroughly. According to the requirements of the new revised version, this added lines and relevant sentences are deleted.

DETAILED COMMENTS

Authors' response: The detailed comments are derived from the referee's marked PDF document by authors. Most of these comments are language grammar issues because the reviewer wants to help the authors to improve the English. Therefore, most of the authors' response are simple except for some important issues.

1. Page 1 Line 15: The $CSPG_{PIT}$ and the $CSPG_{DFIR}$ caught more 3.6% and 2.5% rainfall,

Authors' response: It's true and need not to revise. The $CSPG_{PIT}$ catches more rainfall than the $CSPG_{DFIR}$.

Author's changes in manuscript: No revision.

Spell it out

2. Page 2 Line 14: Its reference is a Mk2 gauge elevated 1 m above the ground and equipped with

Authors' response: It is a British Meteorological Office standard gauge of Snowdon type (Mk2). Mk2 is a type.

Author's changes in manuscript: The reference standard was a British Meteorological Office gauge of the Snowdon type (Mk2) elevated 1 m above the ground and equipped with the Alter wind shield,.....

not clear - lack of wind data at the gauge height?

2. Page 3 Line 6-7: 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

Authors' response: Continuous wind speed measurements was not possible because of the power and instrument problems at the intercomparison site. This part is majorly revised by Dr. E Kang. He is very familiar with this experiments at the Tianshan site.

Author's changes in manuscript: For wind-induced undercatch, the derived CSPG catch ratio equations were based on the 10 m height wind speed at the Daxigou Meteorological Station (43.06°, 86.5°E, 3540 m) and at several other standard meteorological stations near the measurement site (Yang, 1988; Yang et al., 1991). This intensive experimental field study created a basis for later work on the correction of systematic bias in precipitation measurements in China.

3. Page 3 Line 13: (2007) had conducted an intercomparison experiment at 30 sites (altitude varies from about 4.8 m to 3837 m) over China, and they used (using) the pit as reference shield. A total of 29,000 precipitation events had been observed.

Authors' response: This sentence is revised largely.

Author's changes in manuscript: From 1992 to 1998, Ren and Li (2007) conducted an intercomparison experiment at 30 sites (the altitude ranged from about 4.8 to 3837 m) using the pit as a reference across China, and a total of 29, 276 precipitation events were observed.

4. Page 3 Line 29: 1991) to correct the wind-induced errors on Tibetan Plateau. However, their precipitation gauges are Tretyakov, MK2, Nepal2003, Indian and U.S. 8″ in the neighboring countries. As the third pole in the world, the Tibetan

are these gauges ?

Authors' response: Yes, they are. The gauge names are from Table 1 shown by Ma et al. (2014; see below). They said that the instrumental details are derived from Sevruk and Klemm (1989). We look for them in this literature, and find an error: Nepal2003 should be Nepal 203. To avoid confusion, the 'Indian gauge' is revised as 'Indian standard'.

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Precipitation bias variability *versus* various gauges under different climatic conditions over the Third Pole Environment (TPE) region

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Table 1. Nations and corresponding instrumental information over the TPE region.

ID	Country	Gauge type	Setting orifice height (cm)	Area of orifice (cm^2)	Number of selected weather station	Wind-induced error correction procedure
I	Bangladesh	U.S. 8″	70	324	1	Yang *et al.* (1998)
II	China	CSPG	70	314	152	Yang (1988) and Yang *et al.* (1991)
III	India	Indian	30	200	22	No bias-correction result can be referee, dealt by procedure of Tretyakov due to similar size
IV	Kazakhstan	Tretyakov	40	200	9	Goodison *et al.* (1998)
V	Kyrgyzstan	Tretyakov	40	200	7	Goodison *et al.* (1998)
VI	Nepal	Nepal2003	100	324	3	No bias-correction result can be referee, dealt by procedure of U.S. 8″ due to similar size
VII	Pakistan	MK2	30	127	21	Essery and Wilcock (1991)
VIII	Tajikistan	Tretyakov	40	200	9	Goodison *et al.* (1998)
IX	Turkmenistan	Tretyakov	40	200	2	Goodison *et al.* (1998)
X	Uzbekistan	Tretyakov	40	200	15	Goodison *et al.* (1998)

From Sevruk and Klemm (1989):

N_O	Code	Area of orifice A_O [cm^2]	Name	Country of origin	Material	Depth of collector [cm]	Height of gauge [cm]	A_W / A_O
24	20-22-P	200	Indian	India	fibre glass	22	50	4.9
39 *	32-19-S	324	Nepal 203	Nepal	steel	19	59	3.5

Author's changes in manuscript: However, the precipitation gauges used in the neighbouring countries were the Tretyakov, MK2, Nepal203, Indian standard and US 8″.

5. Page 5 Line 16:

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

Authors' response: The word 'gauges' is added.

Author's changes in manuscript: One was a comparison of the $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ gauges.

6. Page 5 Line 22-23:

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

based on ? — not clear — ? for each observation or day ?

Authors' response: They are for each observation.

Author's changes in manuscript: For loss by the CSPG per observation, P_w is 0.23 mm for rainfall measurements, 0.30 mm for snow and 0.29 mm for mixed precipitation (snow with rain, rain with snow), based on the measurements at the Tianshan site (Yang, 1988; Yang et al., 1991).

7. Page 6 Line 2-3:

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

In this field experiment, the different configuration of $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ ~~have~~ used the same P_w, P_e and P_t ~~that have been~~ well quantified constant values as described above. Thus the focus of the present study is the wind-induced error. Wind may be

Authors' response: The 'different configuration of' and 'constant value' are added. The 'have' is replaced by 'used the'. The relevant sentences are also revised.

Author's changes in manuscript: The present study focused on wind-induced bias inprecipitation measurement by CSPGs, specifically in high mountain environments, therefore the above mentioned P_w, P_e and P_t values were assumed to be constant in the computation equations.

8. Page 6 Line 9:

→ please define the catch Ratio [%] as well

(2) $\left(\frac{CSPG_x}{CSPG_{DFIR}}\right)$

(3)

Authors' response: The catch ratio (CR=$CSPG_X$/$CSPG_{DFIR}$, %; X denotes UN, SA or PIT.) is defined in the end of the next paragraph, more suitable place.

Author's changes in manuscript: The catch ratio uses $CSPG_{DFIR}$ as the reference (CR=$CSPG_X$/$CSPG_{DFIR}$, %; X denotes UN, SA or PIT).

9. Page 6 Line 14-15: 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

Authors' response: This sentence is revised according to the above marks.

Author's changes in manuscript: .... As the CMA stations usually observe wind speed at a height of 10m, Eqs.(5)–(7) were used for the CSPG catch ratio versus the daily mean wind speed W_s (ms^{-1}) at 10m (Yang et al., 1991).

10. Page 6 Line 23: 23 cm (Table 2). Few lines should be added related to the fitting method and the use of F-test.

Authors' response: The fitting method and the use of F-test are added in the end of the fifth paragraph in section 2.2. The least version after Editor's comments on August 12, 2015.

Author's changes in manuscript: The equations were fitted using SPSS software version 19.0 (IBM, 2010) and Microsoft Excel 2007 based on the mathematical least squares method (Charnes et al., 1976). The significance of the equations was evaluated using the F-test method (Snedecor and Cochran, 1989). If the significance level (α) of the F-test is below 0.05, the fitted equation is significant. The lower the α value, the greater the significance.

11. Page 7 Line 2: 2 Where Z is 0.7 m or 10 m. denotes the anemometer installation height at

Authors' response: Initially, the 'is' is replaced by the 'denotes the anemometer installation height at'. After Dr. Kang's revision, it is revised as follows.

Author's changes in manuscript: Where *Z* denotes the height referred to

12. Page 8 Line 1: Do we have to repeat all numbers from Table 3? Perhaps would be enough to highlight a few?

Authors' response: The advice is very good. This section is abbreviated as follows.

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

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, respectively, than the $CSPG_{UN}$, and the $CSPG_{PIT}$ and $CSPG_{DFIR}$ caught 3.6% and 2.5% more rainfall, respectively, than the $CSPG_{SA}$. However, the $CSPG_{DFIR}$ caught 1.0% less rainfall than the $CSPG_{PIT}$ (Table 3, Fig.2). These comparative results indicate that the $CSPG_{PIT}$ caught more rainfall and total precipitation compared to the $CSPG_{DFIR}$ and other gauges at the experimental site (Table 3, Fig.2).

The first paragraph of section 3.3 is revised as section 3.2.3 snowfall:

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

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

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

13. Page 9 Line 8-9:

> the limit was decreased,
> 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

Authors' response: 'the limit was decreased' is added in the sentence.

Author's changes in manuscript: ... However, in the Hulu watershed, most snowfall and mixed precipitation events were less than 3.0 mm, thus the limit was reduced and single or daily snowfall and mixed precipitation events greater than 1.0 mm were selected, while rainfall events greater than 3.0 mm were selected.

14. Page 9 Line 8-9: Fig.5 presents scatter plots of the $CR_{UN/DFIR}$ or $CR_{SA/DFIR}$ vs. wind speed. The CRs vary from 80% to 110%. With increasing wind speed, the CRs decreased slightly. The following two equations (10) and (11) could be used to — how was it obtained?

Authors' response: They are from fitting plots Fig.5 by using Microsoft Excel.

Author's changes in manuscript: The text is revised as:

As described in section 2.2, Eq.(10) was fitted using the NONLINEAR function in SPSS software (Analyze\Regression\Nonlinear). The F-value was then calculated using regression and the residual sum of squares from SPSS (Snedecor and Cochran, 1989). Based on the F-value and the degrees of freedom (Df), the significance level (α) was obtained using the FDIST function in Microsoft Excel. Other forms such as the exponential expression were treated in a similar way.

15. Page 9 Line 29-30: 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).

Authors' response: The 'best' is deleted. '3rd order' is replaced by the 'cubic functions'.

Author's changes in manuscript: On the daily scale, the relationships between rainfall CR and wind speed at gauge height ($W_{s0.7}$) are also cubic functions, but they do not pass the F-test with α=0.25 (Table 4).

16. Page 10 Line 1: Ch 3.4: how was it determined if the relationship exponent 2nd or 3rd order or other?

1 **3.4.2 Mixed precipitation catch ratio vs. wind speed**

Authors' response: As described in '10. Page 6 Line 23': The equations were fitted using SPSS software version 19.0 (IBM, 2010) and Microsoft Excel 2007 based on the mathematical least squares method (Charnes et al., 1976). The significance of the equations was evaluated using the F-test method (Snedecor and Cochran, 1989). If the significance level (α) of the F-test is below 0.05, the fitted equation is significant. The lower the α value, the greater the significance.

Author's changes in manuscript: Some lines are added in Page 10 Line 21 in the revised paper: As described in section 2.2, Eq.(10) was fitted using the NONLINEAR function in SPSS software (Analyze\Regression\Nonlinear). The F-value was then calculated using regression and the residual sum of squares from SPSS (Snedecor and Cochran, 1989). Based on the F-value and the degrees of freedom (Df), the significance level (α) was obtained using the FDIST function in Microsoft Excel. Other forms such as the exponential expression were treated in a similar way.

17. Page 11 Line 18:

mixed precipitation were 1.162 (Fig.4b) and 1.082 (Fig.3b), respectively. Similar topographic features and shading induced lower wind speeds at both sites, which led to the similar catch ratios. For the Tianshan reference

Authors' response: The word 'similar' is added.

Author's changes in manuscript: ...... Similar topographic features and shading induced similar lower wind speeds and led to similar catch ratios at both sites. ....

18. Page 12 Line 10-14:

Hulu watershed site. Considering the $CSPG_{PIT}$'s greater simplicity and practicality, it could be more convenient for researchers and observers to use the $CSPG_{PIT}$ as the standard reference for snow and mixed precipitation in other locations. Precipitation collected by the $CSPG_{PIT}$ would be most affected when blowing or drifting snow occurred, and induce a faulty precipitation value (Goodison et al., 1998; Ren and Li, 2007). Previous studies have indicates, however, that for most of China maximum snow depths in the past 30 years have been less than 20 cm (Li, 1999), and average snow depths were less than 3 cm (Li et al., 2008; Che et al., 2008). Fig.8 shows annual

Referee's comments: Add a sentence comparing the maintenance requirements for DFIR & PIT?

Authors' response: The following sentences are added in this paragraph. But it is deleted after Dr. Kang's revision.

Author's changes in manuscript: The pit shield is easy to transit, install, observe and maintain. It occupies only a small place and could be installed in the CMA'S standard meteorological fields, but the DFIR shield is larger and should keep away from the other observations. In the mountains regions, the DFIR shield is difficult to move and install. In addition, the pit shield is only about 150 USD, 6000 USD cheaper than the DFIR shield in China. Therefore, it could be more convenient for researchers and observers to use the $CSPG_{PIT}$ as the standard reference for snow and mixed precipitation in other locations with very low winds.

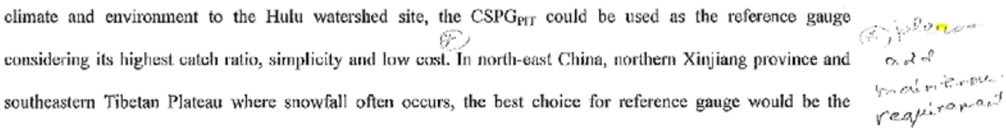
19. Page 13 Line 15-18

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

Authors' response: These sentences are revised according to the above marks. Then it is revised largely.

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

20. Page 13 Line 21:


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

Authors' response: Ok.

Author's changes in manuscript: ... the $CSPG_{PIT}$ could be used as a reference gauge because of its high catch ratio, simplicity and lower maintenance requirements.

21. Page 17 Table 2: Format Better

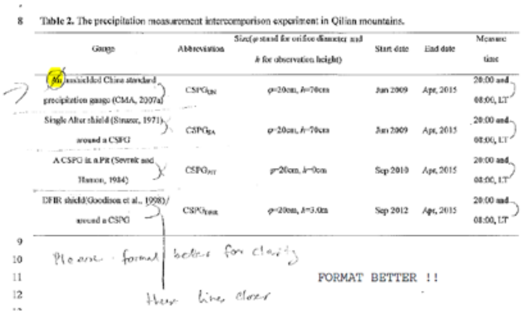


Table 2. The precipitation measurement intercomparison experiment in Qilian mountains.

Authors' response: The original Table 2 is shown as following. The three line table is required by most of the Journals.

Author's changes in manuscript: ...

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

22. Page 18 Table 2: Some lines thicker!

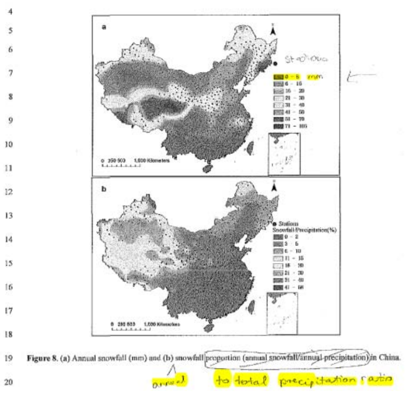
Authors' response: Ok. These lines are thicker. Whether it is suitable, it may be decided by the Journal editors at last.

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

23. Page 27 Figure 8:



Authors' response: The figure appears errors when transferring word version into PDF file. In this revised paper, the figure type is changed.

Author's changes in manuscript: ...

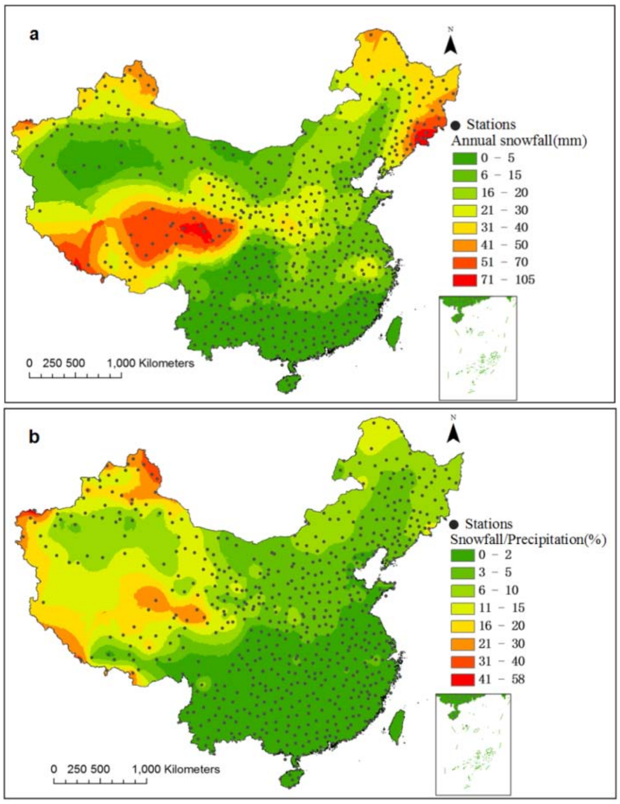


Figure 8. (**a**) Annual snowfall (mm) and (**b**) annual snowfall to total precipitation ratio in China.

(2) Editor comments (August 12, 2015) with marked PDF:

Comments to the Author:

This manuscript has gone through two revisions. The authors have improved this work during each revision. There are, however, still major issues in the revised paper. For example, the regression equations for catch ratio vs wind speed do not include calm conditions, i.e. when wind speed = 0 m/s. For WS = 0 m/s. the equations (presented) would show over or under catch, not CR = 100%. This is not correct physically, as different gauges should measure same amount of precipitation in the calm condition. This is an important test for the regression analyses and results. I recommend the authors to carry out addition data analysis and to consider the condition for zero wind speed.

Authors' response: This is a very important issue, but we have neglected this problem before. All the related equations, tables and figures have been revised according to the above rules. Accordingly, the equations obtaining method is revised. As described in section 2.2 and 3.3:

Section 2.2: The equations were fitted using SPSS software version 19.0 (IBM, 2010) and Microsoft Excel 2007 based on the mathematical least squares method (Charnes et al., 1976). The significance of the equations was evaluated using the F-test method (Snedecor and Cochran, 1989). If the significance level (α) of the F-test is below 0.05, the fitted equation is significant. The lower the α value, the greater the significance.

Section 3.3: As described in section 2.2, Eq.(10) was fitted using the NONLINEAR function in SPSS software (Analyze\Regression\Nonlinear). The F-value was then calculated using regression and the residual sum of squares from SPSS (Snedecor and Cochran, 1989). Based on the F-value and the degrees of freedom (Df), the significance level (α) was obtained using the FDIST function in Microsoft Excel. Other forms such as the exponential expression were treated in a similar way.

Author's changes in manuscript: See detail in the DATILED COMMENTS part.

Comments to the Author:

The quality of presentation also needs significant improvement. There are so many grammar issues in the text. It is difficult to read the text, particularly the new additions from the revision. The responses to reviews are not useful, with many Oks as the short answer. The authors need to communicate their ideas much better than what they have done.

Authors' response: Because most of the 'DETAILED COMMENTS' are grammar issues in the marked PDF file provided by Reviewer #1, thus most of the answers are very simple. We have completed these answers in the new response.

The UK English has been improved by the Armstrong-Hilton Limited during Sep. 22~24, 2015. The revisions are shown in both marked and cleared versions.

Author's changes in manuscript: The Oks is revised in the 'Authors' response'. See detail above. The English is improved according to the latest comments from Editor Dr. Yang and the Armstrong-Hilton Limited. They are shown in the revised version with marks.

Comments to the Author:

I also have many specific comments and questions marked in the attached file. The authors will need to address them in the revision.

Authors' response: These specific comments and questions marked in the attached file are revised.

Author's changes in manuscript: See detail in the following parts.

Comments to the Author:

Non-public comments to the Author:

This is a team work with many authors; some of them (including Dr. Kang) have published many articles in the international journals. I strongly recommend to very carefully editing the text, with the help and input from Dr. Kang. This is the only way to bring this work to the standard of TC.

Please take the time necessary to work on this paper and make it a useful contribution to cold region hydrology research. Please inform the editors if additional time is necessary to complete the data analysis and revision.

Authors' response: Thank you very much. Dr. Kang has revised this paper before the paper is sent to improve English by the Armstrong-Hilton Limited.

Author's changes in manuscript: Dr. Kang has revised the paper including title, abstract, introduction, methods, results, discussion and conclusion sections.

1) **TITLE**: The paper title is revised as "Experimental wind-induced bias in precipitation measurements in a mountain watershed on the north-eastern Tibetan Plateau ".

2) **ABSTRACT is revised as**:

An experimental field study of wind-induced bias in precipitation measurements was conducted from September 2010 to April 2015 at a grassland site (99°52.9′, 38°16.1′, 2980 m) in the Hulu watershed in the Qilian Mountains, on the north-eastern Tibetan Plateau, in China. The experiment included (1) an unshielded Chinese standard precipitation gauge ($CSPG_{UN}$; orifice diameter=20 cm, height=70 cm), (2) a single Alter shield around a CSPG ($CSPG_{SA}$), (3) a CSPG in a pit ($CSPG_{PIT}$) and (4) a Double-Fence International Reference (DFIR) shield with a Tretyakov-shielded CSPG ($CSPG_{DFIR}$). The catch ratio (CR) used the $CSPG_{DFIR}$ as a reference (CR=$CSPG_X$/$CSPG_{DFIR}$, %; X denotes UN, SA or PIT). The results show that the $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DIFR}$ 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 (of all types), respectively, than the $CSPG_{UN}$ from September 2012 to April 2015. The $CSPG_{PIT}$ and $CSPG_{DFIR}$ caught 3.6% and 2.5% more rainfall, 7.3% and 6.0% more mixed precipitation, 4.4% and 8.5% more snowfall and 3.9% and 3.2% more total precipitation, respectively, than the $CSPG_{SA}$. However, the $CSPG_{DFIR}$ caught 1.0% less rainfall, 1.2% less mixed precipitation, 3.9% more snowfall and 0.6% less total precipitation than the $CSPG_{PIT}$. From most to least precipitation measured, the instruments ranked as follows: for rain and mixed precipitation, $CSPG_{PIT}$ > $CSPG_{DFIR}$ > $CSPG_{SA}$ > $CSPG_{UN}$; for snowfall, $CSPG_{DFIR}$ > $CSPG_{PIT}$ > $CSPG_{SA}$ > $CSPG_{UN}$. The CR vs. 10 m wind speed for the period of precipitation indicated that with increasing wind speed from 0 to 8.0m/s, the $CR_{UN/DFIR}$ and $CR_{SA/DFIR}$ for rainfall decreased slightly. For mixed precipitation, the wind speed showed no significant effect on $CR_{UN/DFIR}$ and $CR_{SA/DFIR}$ below 3.5m/s. For snowfall, the $CR_{UN/DFIR}$ and $CR_{SA/DFIR}$ vs. wind speed showed that CR decreased with increasing wind speed. The precipitation measured by the shielded gauges increased linearly relative to that of the unshielded gauges independently of the local environmental conditions. However, the increase in the ratio of the linear correlation should depend on specific environmental conditions. A comparison of the wind-induced bias indicates that the $CSPG_{PIT}$ could be used as a reference gauge for rain, mixed and snow precipitation events at the experimental site. As both the PIT and DFIR effectively prevented wind from influencing the catch of the precipitation gauge, the $CR_{PIT/DFIR}$ had no relationship with wind speed. Cubic polynomials and exponential functions were used to simulate the relationship between catch ratio and wind speed. For snow, for both event and daily scales, the $CR_{UN/DFIR}$ and $CR_{SA/DFIR}$ were significantly related to wind speed; while for rain and mixed precipitation, only the event scale showed a significant relationship.

3) INTRODUCTION

This section is major revised by Dr. Kang as follows.

1 Introduction

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

For decades, all knowledge of precipitation measurement errors has relied on field experiments. Back in 1955, the World Meteorological Organization (WMO) conducted the first precipitation measurement intercomparisons (Rodda, 1973). The reference standard was a British Meteorological Office gauge of the Snowdon type (Mk2) elevated 1 m above the ground and equipped with the Alter wind shield, which did not accurately reflect the precipitation level (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. The gauge in the pit caught 6% more precipitation than the normally exposed gauge. In the second WMO precipitation measurement intercomparison (Rain, 1972–1976), a pit with an 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 gauge 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 standardised adjustment procedure (Lanza et al., 2005). Because automation of precipitation measurements was widespread, the WMO Commission for Instruments and Methods of Observation (CIMO) organised 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 the automatic systems and operational networks for precipitation observations. The experiments and investigations are ongoing, and the WMO-SPICE project confirms the DFIR shield to be a part of the reference configurations.

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

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

The CSPG is the standard manual precipitation gauge that has been used by the China Meteorological Administration (CMA) in more than 700 stations since the 1950s. The present experiment is to investigate the wind-induced bias of the CSPG in the high mountain environment. Therefore, a single Alter shield (SA) (Struzer, 1971), a Double-Fence International Reference shield with a Tretyakov-shielded (DFIR) and a pit were selected to shield the CSPGs, which were distributed by an unshielded CSPG. The SA shield is used by the CMA to enhance the catch ratios of automatic gauges (Yang, 2014), and the DFIR was used to provide true snowfall values for the WMO intercomparison project (Yang et al., 1999). This paper presents the intercomparison experiments and their relevant data, introduces the adjustment methods, discusses wind-induced bias inprecipitation measurements by CSPGs for different precipitation phases, analyses the correlations between shielded and unshielded CSPGs and specifies the relationships between catch ratio and wind speed. The results of the present study are also compared with other studies. In addition, the pit shield is evaluated for solid precipitation under these climatic conditions. The limitations of the present study are then discussed.

4) **EXPERIMENTS AND METHODS**

This part is revised by Dr. Kang, but it is minor.

5) RESULTS

A new section 3.1 **LINEAR CORRELATION OF GAUGE PRECIPITATION** is added.

The structure and description are also revised.

3.1 Linear correlation of gauge precipitation

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

6) DISCUSSION

The paragraph is added in the end of section **4.1 Comparison with other studies**

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

7) CONCLUSION is revised as:

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

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

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

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

Please see the detail in the marked and clear versions.

DETAILED COMMENTS from Editor's comments on August 12, 2015

Authors' response: The detailed comments are derived from the Editor's marked PDF document by authors.

1. Page 7 Line 25: **3.1 Precipitation gauge intercomparison for rainfall** : cut this.

Authors' response: Good advice. After Dr. Kang's revision, it is revised as:

Author's changes in manuscript: 3.2.1 Rainfall

2. Page 8 Line 5:). Comparative studies in This study or other studies (with reference?)

Authors' response: This study.

Author's changes in manuscript: These comparative results indicate that .....

3. Page 8 Line 10: **3.2 Precipitation gauge intercomparison for mixed precipitation** : cut this.

Authors' response: Good advice. After Dr. Kang's revision, it is revised as:

Author's changes in manuscript: 3.2.2 Mixed precipitation

4. Page 8 Line 28: **3.3 Precipitation gauge intercomparison for snowfall** : ddete.

Authors' response: Good advice. After Dr. Kang's revision, it is revised as:

Author's changes in manuscript: 3.2.3 Snowfall

5. Page 9 Line 10-11: mm (Table 3). This suggests that the $CSPG_{PIT}$ could be used as the reference gauge for snow precipitation events at the experiment site.

Editor comments: the more the better? a simply logic that is not always true as other factors may affect gauge catch, like blowing snow into the gauge....

Authors' response: This sentence does not mean the more the better. Firstly, there is a good linear relationship between $CSPG_{PIT}$ and $CSPG_{DIFR}$. Secondly, $CSPG_{DIFR}$ catches more snowfall. Thirdly, the total difference is little (43 snowfall observation, total difference is about 3.4mm) between these two gauges with different configuration. It means that the $CSPG_{PIT}$ could be used as the reference at the experiment site without high wind speed. However, a sentence should be added about blowing snow and wind speed: Blowing snow and thick snow cover have traditionally limited the pit's use as a reference shield for snowfall and mixed precipitation. At the experiment site, the blowing snow was rarely observed and the snow cover was usually shallow.

Author's changes in manuscript: Blowing snow and thick snow cover have traditionally limited the pit's use as a reference shield for snowfall and mixed precipitation. At the experimental site, blowing snow was rarely observed and the snow cover was usually shallow. This suggests that the $CSPG_{PIT}$ could be used as a reference gauge for snow precipitation events at the experimental site.

6. Page 10 Line 5: **3.4.1 Rainfall catch ratio vs. wind speed** : cut

Authors' response: Good advice. This section is revised as follows after Dr. Kang's revision:

Author's changes in manuscript: 3.3 Catch ratio vs. wind speed

7. Page 10 Line 15: Where $CR_{UN/DFIR,Rain}$ and $CR_{SA/DFIR,Rain}$ is the rainfall catch ratio (%) of the $CSPG_{UN}$ and the $CSPG_{SA}$, respectively,

Editor comments: what time scale here???

Authors' response: Per observation.

Author's changes in manuscript: Where $CR_{UN/DFIR,Rain}$ and $CR_{SA/DFIR,Rain}$ is the rainfall catch ratio (%) per observation of the $CSPG_{UN}$ and the $CSPG_{SA}$, respectively,

8. Page 10Line 23: **3.4.2 Mixed precipitation catch ratio vs. wind speed** : cut

Authors' response: Good advice.

Author's changes in manuscript:

9. Page 10 Line 25: t when α<0.10, : not "when" but "at"

Authors' response: Thank you. Total six "when" are replaced.

Author's changes in manuscript: Total six "when" are replaced by "at". But after the English is improved by the company, it is revised as "with".

10. Page 11 Line 14 and others:

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

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

Editor comments:

1) similar to equations below, you need to consider clam condition, i.e. w=0 m/s for the fit..

2) wind can be 0 m/s, then CR is not 100%, meaning over or under catch at calm condition.... this is not right?

3) Ws can be 0 m/s, what happen here if Ws = 0 for the equations here?

Authors' response:

1) Thank you. All the related equations are revised and all the F-value are recalculated. Related tables, figures and equations are revised.

2) Because we should consider the calm conditions, sometimes we should use NONLIEST function in SPSS 19.0. But it did not give the F-value and α value. In this case, we used the SPSS outputs to calculate F-value, then use FDIST function in Microsoft Excel to calculate the α value.

Author's changes in manuscript:

Section 2.2: The equations were fitted using SPSS software version 19.0 (IBM, 2010) and Microsoft Excel 2007 based on the mathematical least squares method (Charnes et al., 1976). The significance of the equations was evaluated using the F-test method (Snedecor and Cochran, 1989). If the significance level (α) of the F-test is below 0.05, the fitted equation is significant. The lower the α value, the greater the significance.

Section 3.3: As described in section 2.2, Eq.(10) was fitted using the NONLINEAR function in SPSS software (Analyze\Regression\Nonlinear). The F-value was then calculated using regression and the residual sum of squares from SPSS (Snedecor and Cochran, 1989). Based on the F-value and the degrees of freedom (Df), the significance level (α) was obtained using the FDIST function in Microsoft Excel. Other forms such as the exponential expression were treated in a similar way.

3) Section 3.3:

a) Eq.(10) is deleted because it is not significant. Eq.(11) is revised as Eq.(10):

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

Eq.(12) and Eq. (13) are revised as Eqs.(11) and (12):

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

$$CR_{SA/DFIR,Mixed} = 100e^{-0.04W_{s10}}$$

$$0<W_{s10}<5.9 \qquad (12)$$

Eq.(14) and Eq. (15) are revised as Eqs.(13) and (14):

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

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

Eq.(18) and Eq. (19) are revised as Eqs.(17) and (18):

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

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

Eq.(20) and Eq. (21) are revised as Eqs.(19) and (20):

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

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

b) Fig.5~Fig. 7 are redrawn:

c) Related tables and text is revised too.

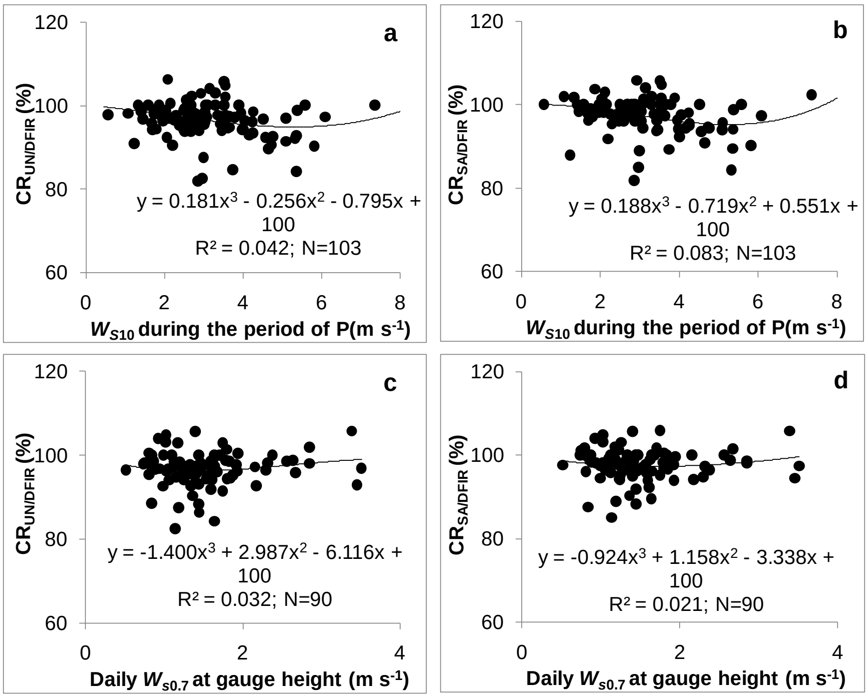


Figure 5. Catch ratios (CRs) vs. wind speed for the rainfall event (**a** and **b**) and the daily rainfall

(**c** and **d**) greater than 3.0 mm.

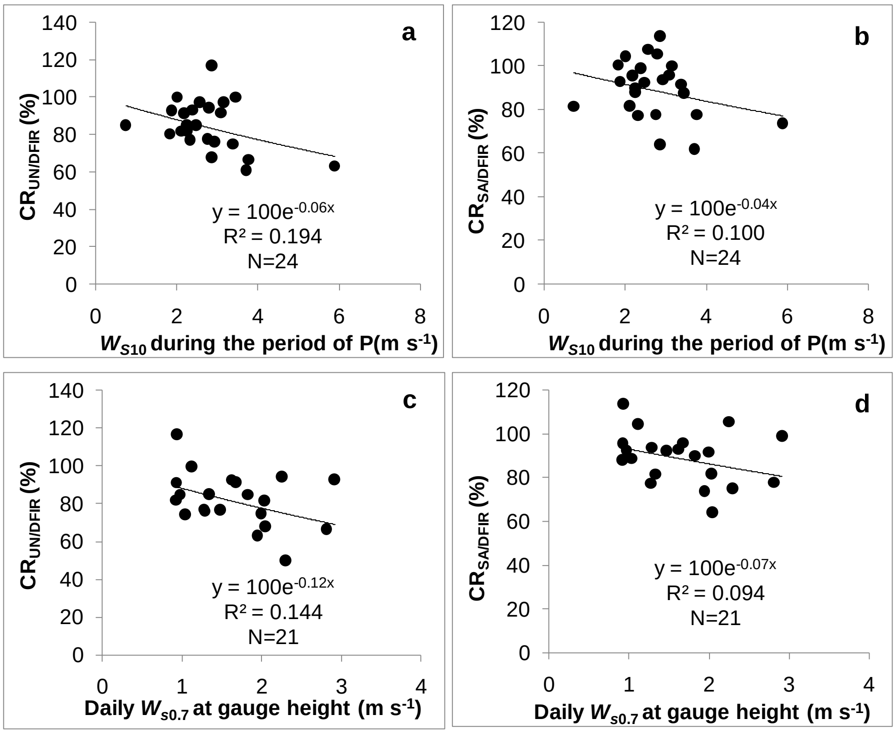


Figure 6. Catch ratios (CRs) vs. wind speed for the mixed precipitation event (**a** and **b**) and the daily mixed precipitation (**c** and **d**) greater than 1.0 mm.

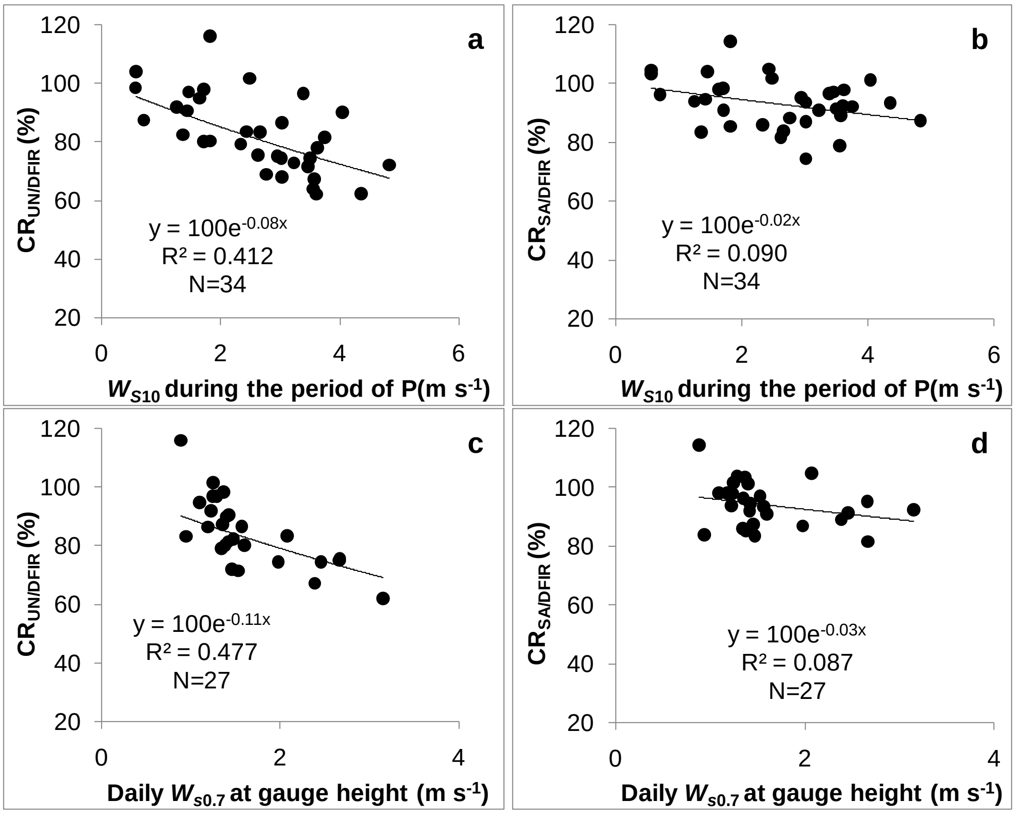


Figure 7. Catch ratios (CRs) vs. wind speed for the snowfall event (**a** and **b**) and the daily (**c** and

d) snowfall greater than 1.0 mm.

d) Table 4 is revised:

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

Temporal scale	Phase	Gauges	~~Best c~~Catch ratio (CR) vs. wind speed relationships*	P (mm)	No. of events	F-test
Precipitation event	Rain	$CSPG_{UN}$	$CR_{UN/DFIR,Rain}=0.181W_{s10}^3-0.256W_{s10}^2-0.795W_{s10}+100$ R²=0.~~070~~042	P>3.0	103	α=0.~~06~~23
		$CSPG_{SA}$	$CR_{SA/DFIR,Rain}=0.188W_{s10}^3-0.719W_{s10}^2+0.551W_{s10}+100$ R²=0.~~099~~083			α=0.~~01~~03
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Rain}=0.150W_{s10}^3-0.425W_{s10}^2+1.119W_{s10}+100$ R²=0.~~023~~008			α=0.~~50~~83
	Mixed	$CSPG_{UN}$	$CR_{UN/DFIR,Mixed}=100e^{-0.06W_{s10}}$ R²=0.~~198~~194	P>1.0	24	α=0.07
		$CSPG_{SA}$	$CR_{SA/DFIR,Mixed}=100e^{-0.04W_{s10}}$ R²=0.~~102~~100			α=0.16
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Mixed}=100e^{-7E-0W_{s10}}$ R²=0.~~023~~000			α=~~0.47~~no data
	Snow	$CSPG_{UN}$	$CR_{UN/DFIR,Snow}=100e^{-0.08W_{s10}}$ R²=0.~~420~~412	P>1.0	~~32~~34	α=~~4.7~~6.4E-05
		$CSPG_{SA}$	$CR_{SA/DFIR,Snow}=100W_{s10}^{-0.02}$ R²=0.~~122~~090			α=0.~~04~~07
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Snow}=100e^{-0.01W_{s10}}$ R²=0.~~110~~024			α=0.~~30~~35
Daily precipitation	Rain	$CSPG_{UN}$	$CR_{UN/DFIR,Rain}=-1.400W_{s0.7}^3+2.987W_{s0.7}^2-6.116W_{s0.7}+100$ R²=0.~~045~~032	P>3.0	90	α=0.~~26~~37
		$CSPG_{SA}$	$CR_{SA/DFIR,Rain}=-0.924W_{s0.7}^3+1.158W_{s0.7}^2-3.338W_{s0.7}+100$ R²=0.~~031~~021			α=0.~~43~~55
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Rain}=-0.952W_{s0.7}^3-1.503W_{s0.7}^2+2.237W_{s0.7}+100$ R²=~~0.017~~ 0.00			α=~~0.68~~no data
	Mixed	$CSPG_{UN}$	$CR_{UN/DFIR,Mixed}=100e^{-0.12W_{s0.7}}$ R²=0.~~169~~144	P>1.0	21	α=0.09~~6~~
		$CSPG_{SA}$	$CR_{SA/DFIR,Mixed}=100e^{-0.07W_{s0.7}}$ R²=0.~~122~~094			α=0.~~12~~18
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Mixed}=100e^{-0.001W_{s0.7}}$ R²=0.~~017~~003			α=~~0.60~~no data
	Snow	$CSPG_{UN}$	$CR_{UN/DFIR,Snow}=100e^{-0.11W_{s0.7}}$ R²=0.~~577~~477	P>1.0	27	α=~~5.7~~1.8E-~~6~~04
		$CSPG_{SA}$	$CR_{SA/DFIR,Snow}=100e^{-0.03W_{s0.7}}$ R²=0.~~111~~087			α=0.~~09~~14
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Snow}=100e^{-0.01W_{s0.7}}$ R²=~~0.134~~ 0.00			α=~~0.33~~no data

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

11. Page 12 Line 10-15: shading induced similar lower wind speeds at both sites, which led to the similar catch ratios. For the Tianshan reference site, wind speed (W_{s10}) on rainfall or snowfall days never exceeds 6 m s^{-1} and 88% of the yearly total precipitation took place with wind speeds below 3 m s^{-1}. For the Hulu watershed site, daily mean wind speeds ($W_{s0.7}$) on precipitation days never exceeded 3.5 m s^{-1}, and over 98.9% of the precipitation events occurred when daily mean wind speeds were below 3 m s^{-1}. During the period of precipitation, the largest wind speed at 10 m

Editor comments: compare winds at 10 and 0.7 m, not right!

Authors' response: Thank you. This paragraph is rewritten. The daily mean wind speed at 10 m is used to compare.

Author's changes in manuscript: Similar topographic features and shading induced similar lower wind speeds and led to similar catch ratios at both sites. For the Tianshan reference site, wind speed (W_{s10}) on rainfall or snowfall days never exceeded 6 m s^{-1}, and 88% of the total annual precipitation took place with wind speeds below 3 m s^{-1}. At the Hulu watershed site, daily mean wind speeds (W_{s10}) on precipitation days never exceeded 6.4 m s^{-1}, and over 55.2% of the precipitation events occurred with daily mean wind speeds below 3 m s^{-1}. During the periods of precipitation, the largest wind speed at the 10m height was about 8.8 m s^{-1}, and over 54.2% of the precipitation events occurred with wind speeds below 3 m s^{-1}.

12. Page 12Line 24: the different wind regime.

Editor comments: discuss wind regimes then, like mean winds for the sites....

Authors' response: The daily mean wind speeds at 10 m height were analyzed on precipitation days during the experimental period from 1992 to 1998.

Author's changes in manuscript: At the Gangcha station (100°08′, 37°20′, 3015 m), which also lies in the Qilian Mountains at a similar elevation about 200 km 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 $CSPG_{PIT}$ captured 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 that reported by Ren et al. (2003) due to differences in the wind regime. At the Gangcha station, daily mean wind speeds (W_{s10}) on precipitation days during the experimental period from 1992 to 1998 never exceeded 8.5 m s^{-1}, and over 35.1% of the precipitation events occurred with daily mean wind speeds below 3 m s^{-1}. The average daily mean W_{s10} was about 3.4 m s^{-1} on precipitation days from 1992 to 1998 at the Gangcha station, whereas at the Hulu watershed site from 2010 to 2015, the average value was about 2.9 m s^{-1} on precipitation days.

13. Page 13Line 17: than 15% of the annual precipitation amount. Ren and Li (2007) has reported, among the 29276 precipitation events, there are only 784 blowing or drifting snow events accounting to about 2.7% at the 30 stations over China.

Editor comments: this is over entire China, no snow then no blowing snow, you need to look into the cold regions WITH snow???

Authors' response: We looked into the original literature and found that the 784 blowing or drifting snow events here was wrong, it should be 54 events (Ren et al., 2003). The value 784 is total eliminated events including missing observation, blowing snow, etc. Thus, the blowing or drifting snow events ratio is about 0.18% (54/29276). For snowfall, the total snowfall events is 2286, and the blowing or drifting snow events ratio is about 2.4%. There was no snowfall event from 1992 to 1998 at the four stations among the 30 stations. Two references are replaced by the two new papers. Thus, this sentence is revised as follows.

Author's changes in manuscript: Ren et al. (2003) reported, that among the 2286 snowfall events, only 54 were blowing or drifting snow events accounting for about 2.4% for 26 stations across China. Based on the regionalisation of snow drift in China, blowing or drifting snow events occur mostly on the central and south-western Tibetan Plateau, in the northern Xinjiang province and in north-eastern China (Wang and Zhang, 1999).

14. Page 13 Line 20: province and north-eastern China (Ren et al., 2003). The applicable regions for the $CSPG_{PIT}$ and the $CSPG_{DFIR}$ as reference gauges are shown in Fig.9 based on CMA snowfall and snow depth data.

Editor comments: you suggest, pit gauge for rain regions and DFIR for snow regions? make this clear if you agree....

Authors' response: The DFIR is used in the regions with much blowing or drifting snow events, while the pit, other regions.

Author's changes in manuscript: In these regions, the $CSPG_{DFIR}$ should be used as a reference gauge. In other regions, the $CSPG_{PIT}$ may be applicable. Based on the CMA snowfall and snow depth data, and the regionalisation of snow drift in China, the applicable regions for the $CSPG_{PIT}$ and $CSPG_{DFIR}$ as reference gauges are shown in Fig.10.

15. Page 14 Line 5: 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

Editor comments: how was Z_0 determined here??? give more info....

Authors' response: Z_0 is calculated by using the Eqs.(9).

Author's changes in manuscript: For the precipitation period from September 2012 to April 2015, the Z_0 was calculated using Eq. (9). The results showed the Z_0 to be about 0.06m on average but it varied from nearly zero to 0.67m.

16. Page 14 Line 7: 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).

Editor comments: compare and cite other studies.....

Authors' response: There are many statistical ways to deal with this issue. Here use a equation provided by Lettau (1969): $Z_0=0.5hL_e$. h is the vegetation height and L_e is vegetation coverage. At the field site, the vegetation coverage is close to 100% in summer and autumn. The very large Z_0 values also appear in the later August and early September (From most to the least, Z_0 appears day: Sep 8, 2013 (0.67); Sep16, 2014 (0.58); Sep 13, 2014 (0.51); Aug 29, 2014 (0.47); May 16, 2013 (0.47); Sep 7, 2014 (0.43), ...).

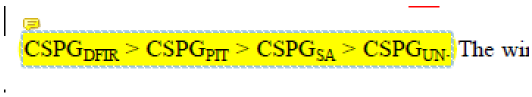
Author's changes in manuscript: As shown in Fig.11, in about 68.9% and 95.1% of instances, the Z_0 was lower than 0.05 m and 0.25 m, respectively. In rare cases when the Z_0 was very large, as shown in Fig.11, the Z_0 was arbitrarily assigned 1/2 of the grass height (*h*) at the site based on the equation $Z_0=0.5hL_e$ provided by Lettau (1969). The very large Z_0 values usually appeared in late August and early September when the vegetation coverage (L_e) was close to 100% at the Hulu watershed site.

17. Page 14 Line 12: The precipitation intercomparsion experiment in the Hulu watershed indicates that the $CSPG_{PIT}$ catches more rainfall, mixed precipitation and total precipitation than the $CSPG_{DFIR}$. From most to the least rainfall and mixed

Editor comments: BUT LESS snow, that is the key, DFIR is for snowfall, not for rain......

Authors' response: It's true.

Author's changes in manuscript: The precipitation intercomparison experiment in the Hulu watershed of the Qilian Mountains indicated that the $CSPG_{PIT}$ caught more rainfall, mixed precipitation and total precipitation but less snowfall than the $CSPG_{DFIR}$.

18. Page 14 Line 15: 
$CSPG_{DFIR}$ > $CSPG_{PIT}$ > $CSPG_{SA}$ > $CSPG_{UN}$. The wi

Editor comments: Pit gauge is for rain, maybe ok for wet snow in summer.... do you look at the winter snow data vs. summer wet snow?

Authors' response: The snowfall in winter at the experiment site is relatively few and less than in other seasons. We would add a figure and talk it about in section "4.2 $CSPG_{PIT}$ as a reference for solid precipitation".

Author's changes in manuscript: In section "4.2 $CSPG_{PIT}$ as a reference for solid precipitation": The snowfall is wetter in autumn and spring than in winter, and wetter snowfall means less blowing or drifting snow. Thus the $CSPG_{PIT}$ could serve as a reference for liquid and solid precipitation in environments similar to that of the Hulu watershed site.

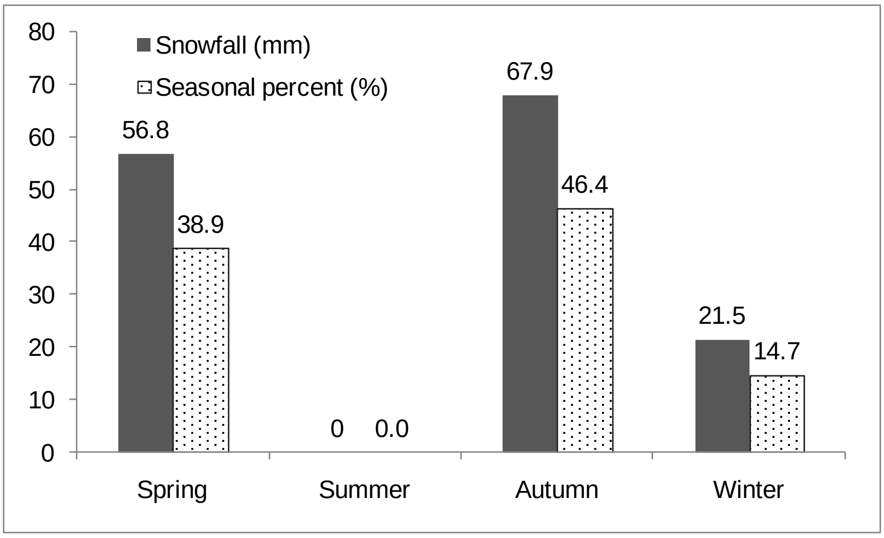


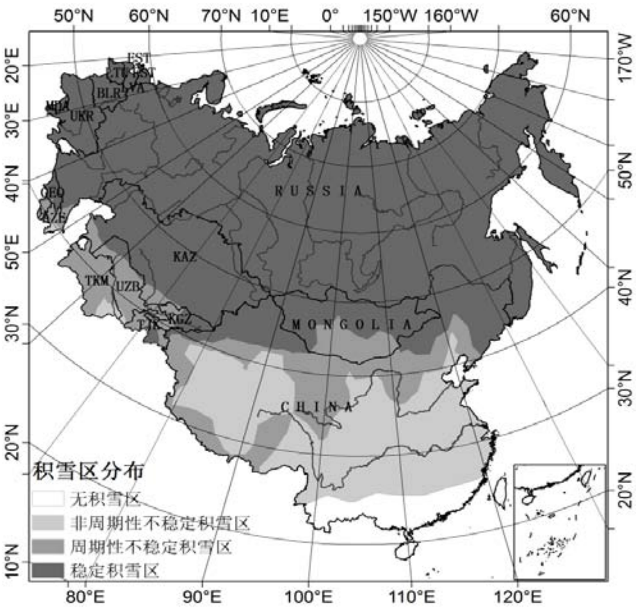
Figure 8. Seasonal snowfall and its percent from September 2010 to April 2015 at the Hulu watershed site.

19. Page 14Line 18: In the regions with little snowfall such as the south and central part of China,

Editor comments: warm climate without snow, no snowfall undercatch? why DFIR there?????

Authors' response: Snowfall does occur in the most regions of China except for very few province such as the Hainan province. It appears even in Fujian, Guangdong province, etc. See the figure below (Zhang and Zhong, 2014) and Fig.9.

Author's changes in manuscript: In regions with lower snowfall, such as the southern and central parts of China (Zhang and Zhong, 2014), and in regions with a similar climate and environment to that of the Hulu watershed site, the $CSPG_{PIT}$ could be used as a reference gauge because of its high catch ratio, simplicity and lower maintenance requirements.



(Zhang and Zhong, 2014. Journal of Glaciology and Geocryology, 36, 481-490)

20. Page 19Table 1:

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

Editor comments: very low winds......

Authors' response: We have looked into the observation data and computer program. It is a statistical error. It was wrongly divided by 3. The computer program has selected all the data by day and month time and then obtained their mean values. It need not divide them by 3 years again.

The air temperature is also wrongly calculated. They use and in a same computer program. Other variables such as precipitation and potential evaporation are correct and need not revise. We are very sorry and thank you very much.

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

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

Element	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
Monthly precipitation (mm)	3.5	2.5	11.0	8.8	67.7	69.6	87.1	111.6	57.7	24.0	2.7	1.0	447.2
Monthly mean air temperature (^{o}C)	-12.4	-7.7	-4.4	2.2	7.0	11.2	12.5	12.1	8.0	1.4	-5.6	-11.3	1.1
Monthly mean daily maximum air temperature (^{o}C)	-4.0	0.7	3.5	10.3	14.3	18.2	19.5	19.7	15.4	10.2	3.6	--1.9	9.1
Monthly mean daily minimum air temperature (^{o}C)	-19.0	-14.8	-11.6	-5.2	0.6	4.9	6.8	5.8	1.8	-5.5	-12.7	-18.2	-5.6
Monthly mean wind speed at the 1.5m height ($m\ s^{-1}$)	1.79	1.96	2.30	2.55	2.42	1.98	1.82	1.81	1.93	1.81	2.08	1.96	2.03
Monthly mean wind speed at the 2.5m height ($m\ s^{-1}$)	1.79	2.02	2.43	2.77	2.65	2.16	2.04	2.02	2.16	1.99	2.19	2.01	2.18
Monthly potential evaporation (mm)	31.6	47.0	79.4	124.4	140.9	155.0	141.7	127.0	101.6	75.2	47.3	31.0	1102.2

21. Page 26 Fig.5:

Editor comments: for a) and b), no data for winds 8-10m/s, that part (ratio going up) is very uncertain? need to think of other models for the fit?

Authors' response: All the related figures, tables and equations are revised because the calm condition when Ws=0 is not considered before.

Author's changes in manuscript: See the detail above.

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

~~Precipitation measurement intercomparison in the Qilian Mountains, Northeastern Tibetan Plateau~~

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Abstract: An experimental field study of wind-induced bias in precipitation measurements was conducted from September 2010 to April 2015 at a grassland site (99°52.9′, 38°16.1′, 2980 m) in the Hulu watershed in the Qilian Mountains, on the north-eastern Tibetan Plateau, in China. ~~Systematic errors in gauge-measured precipitation are well-known, but the wind-induced error of Chinese standard precipitation gauge (CSPG) has not been well tested. An intercomparison experiment was carried out from September 2010 to April 2015 in the Hulu watershed, northeastern Tibet Plateau~~. ~~Precipitation gauges included~~The experiment included (1) an unshielded Chinese standard precipitation gauge~~CSPG~~ (CSPG$_{UN}$; orifice diameter=20 cm, height=70 cm), (2) a single Alter shield around a CSPG (CSPG$_{SA}$), (3) a CSPG in a pit (CSPG$_{PIT}$) and (4) a Double-Fence International Reference (DFIR) shield with a Tretyakov-shielded CSPG (CSPG$_{DFIR}$). The catch ratio (CR) uses CSPG$_{DFIR}$ as a reference (CR=CSPG$_X$/CSPG$_{DFIR}$, %; X denotes UN, SA or PIT). ~~The intercomparison experiments~~ The results show that the CSPG$_{SA}$, CSPG$_{PIT}$~~,~~ and 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 (of all types), respectively, than the CSPG$_{UN}$ from September 2012 to April 2015~~, respectively~~. The CSPG$_{PIT}$ and ~~the~~ CSPG$_{DFIR}$ caught ~~more~~ 3.6% and 2.5% more rainfall, 7.3% and 6.0% more mixed precipitation, 4.4% and 8.5% more snowfall~~,~~ and 3.9% and 3.2% more total precipitation, respectively, than the CSPG$_{SA}$~~, respectively~~. ~~Whereas~~ However, the CSPG$_{DFIR}$ caught 1.0% less rainfall, 1.2% less mixed precipitation, 3.9% more snowfall and 0.6% less total precipitation than the CSPG$_{PIT}$~~, respectively~~. From most to least precipitation measured, the instruments ranked as follows: for rain and mixed precipitation, CSPG$_{PIT}$ >

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$CSPG_{DFIR}$ > $CSPG_{SA}$ > $CSPG_{UN}$; for snowfall, $CSPG_{DFIR}$ > $CSPG_{PIT}$ > $CSPG_{SA}$ > $CSPG_{UN}$. ~~From most to least rain and mixed precipitation, the measurements are ranked as follows: $CSPG_{PIT}$ > $CSPG_{DFIR}$ > $CSPG_{SA}$ > $CSPG_{UN}$. For the snowfall, it follows as: $CSPG_{DFIR}$ > $CSPG_{PIT}$ > $CSPG_{SA}$ > $CSPG_{UN}$. The $CSPG_{DFIR}$ is used as reference to calculate the catch ratios (CRs) of the $CSPG_{UN}$, $CSPG_{SA}$ and $CSPG_{PIT}$.~~ The CR vs. 10m wind speed ~~during~~ for the period of precipitation ~~indicates~~ indicated that with increasing wind speed from 0 to 8.0m/s, the ~~rainfall~~ $CR_{UN/DFIR}$ ~~or~~ and $CR_{SA/DFIR}$ for rainfall decreased slightly. For ~~the~~ mixed precipitation, wind speed ~~has~~ showed no significant effect on $CR_{UN/DFIR}$ ~~or~~ and $CR_{SA/DFIR}$ below 3.5m/s. For ~~the~~ snowfall, the $CR_{UN/DFIR}$ ~~or~~ and $CR_{SA/DFIR}$ vs. wind speed ~~shows~~ showed that CR ~~decreases~~ decreased with increasing wind speed. The precipitation measured by shielded gauges increased linearly relative to that unshielded gauges independently of the local environmental conditions. However, the increase in the ratio of the linear correlation should depend on specific environmental conditions. A comparison of the wind-induced bias indicates that $CSPG_{PIT}$ could be used as a reference gauge for rain, mixed and snow precipitation events at the experimental site. As both the PIT and DFIR effectively prevented wind from influencing the catch of the precipitation gauge, the $CR_{PIT/DFIR}$ had no relationship with wind speed. Cubic polynomials and exponential functions were used to simulate the relationship between catch ratio and wind speed. For snow, for both event and daily scales, the $CR_{UN/DFIR}$ and $CR_{SA/DFIR}$ were significantly related to wind speed; while for rain and mixed precipitation, only the event scale showed a significant relationship.

~~The adjustment equations for three different precipitation types for the $CSPG_{UN}$ and $CSPG_{SA}$ were established based on the CR vs. wind speed analysis and World Meteorological Organization (WMO) recommended procedure. They would help to improve the current bias error-adjusted method and precipitation accuracy in China. Results indicate that combined use of the $CSPG_{DFIR}$ and the $CSPG_{PIT}$ as reference gauges for snowfall and rainfall, respectively, could enhance precipitation observation precision. Applicable regions for the $CSPG_{PIT}$ or the $CSPG_{DFIR}$ as representative gauges for all precipitation types are present in China.~~

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

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1 Introduction

In western China, mountainous watersheds are the source areas of runoff generation and water resources, and accurate precipitation measurements are extremely important for calculating the water balance and understanding the water cycle processes in these high mountains. ~~Accurate precipitation data are necessary for better understanding of the water cycle.~~ It is widely recognised~~It has been widely recognized~~ that gauge-measured precipitation has systematic errors, mainly caused by wetting, evaporation losses and wind-induced undercatch, and snowfall observation errors are very large under high wind (Sugiura et al., 2003). These errors affect the available water evaluation in a large number of economic and environmental applications (Tian et al., 2007; Ye et al., 2012).

For decades, all knowledge of precipitation measurement errors has relied on field experiments. Back in 1955, the World Meteorological Organization (WMO) conducted the first precipitation measurement intercomparisons (Rodda, 1973). ~~Its~~ The reference standard ~~i~~was a British Meteorological Office gauge of the Snowdon type (Mk2)~~Mk2 gauge~~ elevated 1 m above the ground and equipped with the Alter wind shield,~~. But this reference~~ which ~~does~~ did not accurately ~~show the correct amount of~~reflect the precipitation level~~. 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~~ The gauge in ~~a~~ the pit caught 6% more precipitation than the normally exposed gauge. In the second WMO precipitation measurement intercomparison (Rain, 1972–1976), ~~the~~ a pit with an 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 gauge~~s~~ 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~~ standardised adjustment procedure (Lanza et al., 2005). Because automation of precipitation measurements ~~are~~ is 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 the automatic systems and ~~the~~ operational networks for precipitation observations. The experiments and investigations are ongoing, and the WMO-SPICE project ~~still selected~~ confirms the DFIR shield to be a part of the reference configurations. ~~The WMO-SPICE project still selected DFIR shield as part of the reference configurations.~~

The DFIR shield has been operated~~ as part of reference configurations~~ at 25 stations in 13 countries around the world (Golubev, 1985; Sevruk et al., 2009), but deviations from the DFIR measurements vary by gauge type and precipitation type (Goodison et al., 1998). In China, the Chinese standard precipitation gauge (CSPG) and the Hellmann gauge were first~~ly~~ compared ~~by~~ using the DFIR shield as a reference configuration~~s~~ ~~in~~ at the ~~valley~~ Tianshan site~~ of Tianshan~~ (43°7′ N, 86°49′ E, 3720 m), during the third WMO precipitation measurement intercomparison experiment from 1985 to 1987 (Yang, 1988; Yang et al., 1991). The wetting loss, evaporation loss~~es~~, wind-induced undercatch and trace precipitation of the CSPGs were well quantified based on the huge volume of observation data at the Tianshan site (Yang et al., 1991). ~~Because there are not wind data at the intercomparison site (Yang et al., 1991; Goodison et al., 1998), for~~ 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~~;~~) and at several other standard meteorological stations near the measurement site (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~~. This intensive experimental field study created a basis for later work on the correction of systematic bias in precipitation measurements in China. During the period from 1992 to 1998, Ren and Li (2007) ~~had~~ conducted an intercomparison experiment at 30 sites (the altitude ~~varies~~ ranged from about 4.8 ~~m~~ to 3837 m) using the pit as a reference across~~over~~ China, and ~~A~~a total of 29,~~000~~276 precipitation events ~~had been~~were observed. Yang et al. (1999) emphasised that among all known systematic errors in precipitation observation, wind-induced gauge undercatch was the greatest source of bias, particularly in cold regions, and recommended testing for the application of adjustment techniques in regional observation networks. In the mountainous watersheds of western China, the complex high mountain topography and underlying surfaces with inhomogeneous glaciers, permafrost and alpine vegetation make the wind vector field in the lower boundary layer extremely complex, causing equally complex wind field deformations over the gauge orifice. At present, our investigation of wind-induced error in precipitation measurements is based on the horizontal time-averaged wind speed. Thus it is reasonable to investigate the regional average characteristics of wind fields and the interaction between wind fields and the precipitation gauges at our present research level. In addition to Yang's experimental field work on systematic error adjustments for precipitation measurements in eastern Tianshan from 1985 to 1987 (Yang, 1988), it is very important to carry out field experiments on precipitation measurement in the other mountainous regions of western 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 a~~Adjustment procedures and reference measurements were developed ~~in~~ during several WMO international precipitation measurement intercomparisons (Goodison et al., 1998; Sevruk et al., 2009; Yang, 2014). The application of all of these adjustment procedures and methods depends on both environmental factors and precipitation features, and among the factors considered, wind speed and temperature have been found to have the most important effect on gauge catch (Yang et al., 1999). Ye et al. (2004, 2007) developed a bias-error adjustment method for CSPGs based on observation data from 1985 to 1997 at the Tianshan site (Yang et al., 1991), and found a new precipitation trend in the adjusted precipitation data for the past 50 years in China (Ding et al., 2007). The new precipitation adjustment has improved the precipitation estimation in water balance computation for many basins in China (Ye et al., 2004; Tian et al., 2007; Ye et al., 2012).~~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 neighbouring countries ~~except for~~in addition to the experimental results from the eastern Tianshan ~~Tianshan~~in China (Yang et al., 1991) to correct for the wind-induced errors on Tibetan Plateau. However, their precipitation gauges used in the neighbouring countries were the ~~are~~ Tretyakov, MK2, Nepal 20~~0~~3, Indian standard and U.S. 8″ ~~in the neighboring countries~~. As the world's third pol~~e~~ar region ~~in the world~~, the Tibetan Plateau and its surrounding mountain ranges are ~~is an~~ ecologically fragile ~~region~~ and the source of several large rivers in China and neighbouring countries, and accurate precipitation data are urgently needed for water resource exploitation and environmental protection. The problem is how to apply and test the already established principal adjustment procedures and methods to correct for precipitation measurement errors in the vast plateau and high mountains of western China, where climatic and environmental conditions are highly complex and variable, both spatially and temporally. To quantify and understand the specific influences of climatic and environmental factors on wind-induced bias in precipitation measurements in a mountain watershed, and then test and parameterise the adjustment equations, an intercomparison experiment was carried out for nearly five years on both unshielded and shielded CSPGs in a watershed in the Qilian Mountains on the north-eastern Tibetan Plateau in China.

~~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 that has been used by the China Meteorological Administration (CMA) ~~at~~ in more than 700 stations since the 1950s. The present experiment is to investigate the wind-induced bias of the CSPG in the high mountain environment. ~~These precipitation data sets have been used widely and need to be adjusted by using better methods.~~ Therefore, ~~The~~ a ~~Single~~ 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.~~ , a Double-Fence International Reference shield with a Tretyakov-shielded (DFIR) and a pit were selected to shield the CSPGs, which were distributed by an unshielded CSPG. The SA shield is used by the CMA to enhance the catch ratios of automatic gauges (Yang, 2014), and the DFIR was used to provide true snowfall values for the WMO intercomparison project (Yang et al., 1999). This paper presents the intercomparison experiments and their relevant data, introduces the adjustment methods, discusses wind-induced bias inprecipitation measurements by CSPGs for different precipitation phases, analyses the correlations between shielded and unshielded CSPGs and specifies the relationships between catch ratio and wind speed. The results of the present study are also compared with other studies. In addition, the pit shield is evaluated for solid precipitation under these climatic conditions. The limitations of the present study are then discussed.

~~The CSPG$_{DFIR}$ was selected as the reference for all precipitation types. The intercomparison experiments tested and assessed existing bias adjustment procedures for the CSPG$_{UN}$ and the SA shield around a CSPG (CSPG$_{SA}$).~~

2 Experiments and methods~~Data and Methods~~

2.1 Intercomparisons ~~experiments~~ and ~~relevant~~ data

Precipitation intercomparison experiments (Fig.1, Table 1) were conducted at a grassland site~~–~~ (99°52.9′, 38°16.1′, 2980 m) in the Hulu watershed in the Qilian mountains, on the north-eastern edge of the Tibetan Plateau, in China ~~(99°52.9′, 38°16.1′, 2980 m)~~. A meteorological cryosphere-hydrology observation system (Chen et al., 2014a) ~~has been~~was established ~~since~~ in 2008 in the Hulu watershed. The Mean ~~A~~annual precipitation ~~is~~ was ~~about~~ 447.2 mm during 2010-2012 and ~~is~~ was concentrated during the warm season from May to September ~~at this site~~. The annual mean temperature ~~is~~ was ~~approximately 0.4~~1.1 °C, with a July mean (T_{mean}) of ~~4.2~~12.5 °C and a January mean of -~~4.1~~12.4°C over the years (Table 1). The annual potential evaporation ~~ability (E_0)~~ ~~is~~ was ~~about~~ 1102 mm (Table 1).

The intercomparative~~intercomparison~~ experiments included (1) an unshielded CSPG (CSPG$_{UN}$; orifice diameter=20 cm, height=70 cm), (2) a single Alter shield around a CSPG (CSPG$_{SA}$), (3) a CSPG in a pit

(CSPG$_{PIT}$), and (4) a 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), snowfalls ~~dominated~~ dominated the precipitation events, and in the warm season (May to September), rainfall was dominate~~d~~d. The precipitation ~~amount (*P*) is~~ was measured manually twice a day at 08:00 and 20:00 ~~LT~~ local time (Beijing time) according to the CMA's ~~criterion~~ criteria (CMA, 2007a). In the warm season, ~~*P*~~ precipitation ~~is~~ was measured by volume. ~~In~~ Whereas in the cold season, the funnel and glass bottle ~~are~~ were removed from the CSPG and precipitation ~~is~~ was weighed under a windproof box~~ to avoid wind effects~~. I~~f there is~~Any frost on the outside surface of the collector~~, it will be~~ was wiped ~~up by off~~using a dry hand towel. In rare cases where snow had accumulated on the rim of the collector, this was removed before weighing. ~~In the rare cases of snowfall accumulating on the rim of the collector, half of them (semi circular) will be removed before they are weighted.~~

The precipitation phases (snow, rain and mixed) ~~is~~ were distinguished using ~~discriminated by observer according to~~ the CMA's ~~criterion~~ criteria(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.~~

Meteorological elements, including maximum air temperature T_{max} and minimum T_{min}, have been measured conforming to the meteorological observation manual~~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 meteorological tower ~~is~~ was used to measure wind speed (Lisa/Rita, SG GmbH; W_s) ~~and~~ , air temperature (HMP45D, Vaisala) and relative humidity (HMP45D, Vaisala) at 1.5m and 2.5m heights in association with ~~relative humidity (HMP45D, Vaisala) and~~ precipitation measurement (Chen et al., 2014). The time step of observation of the tower was~~They are observed every~~ 30 seconds and ~~are saved as~~the –half-hourly values ~~(sum or mean)~~were obtained. 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~~ focused on two key aspects. One ~~is~~ was a comparison~~s~~ ~~among~~ of the CSPG$_{UN}$, CSPG$_{SA}$, CSPG$_{PIT}$ and CSPG$_{DFIR}$ gauges. The other was the establishment of~~Another purpose is to establish~~ adjustment equations for the CSPG$_{UN}$ and ~~the~~ CSPG$_{SA}$ ~~by~~ using the CSPG$_{DFIR}$ as a reference. To adjust ~~the~~ gauge-measured precipitation, Sevruk and Hamon (1984) ~~have~~ provided~~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~~ 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 the DFIR-~~shielding~~ shielded precipitation. For loss by the CSPG per observation, P_w is 0.23 mm for rainfall measurements, 0.30 mm for snow and 0.29 mm for mixed precipitation (snow with rain, rain with snow) ~~(Yang, 1988; Yang et al., 1991)~~, ~~according to~~based on the measurements ~~in~~ at the Tianshan ~~valley~~ site (Yang, 1988; Yang et al., 1991). Ren and Li (2007) reported ~~the~~ a mean P_w ~~was~~ of 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~~ from 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. The present study focused on wind-induced bias inprecipitation measurement by CSPGs, specifically in high mountain environments, therefore the above mentioned P_w, P_e and P_t values were assumed to be constant in the computation equations.

~~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.~~

WMO proposed Eqs.(2)-(4) to compute the catch ratio of unshielded over shielded Tretyakov gauges on a daily time step for three precipitation types, and the independent variables were wind speed (W_s, m s^{-1}) at the gauge height and the daily maximum and minimum temperatures (T_{max}, T_{min}, °C)~~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~~are 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).

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

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

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

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

Wind speeds at gauge height ($W_{s0.7}$) and at the 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 where Z denotes the height referred to is 0.7 m or 10 m.

3 Results

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

Table 3 about here

3.1 Linear correlation of gauge precipitation

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

Fig.2 about here

Fig.3 about here

Fig.4 about here

3.2 Comparison of the wind-induced bias

3.~~1~~ 2.1 ~~Precipitation gauge intercomparison for rainfall~~ 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, respectively, than the $CSPG_{UN}$, and the $CSPG_{PIT}$ and $CSPG_{DFIR}$ caught more 3.6% and 2.5% rainfall, respectively, than the $CSPG_{SA}$~~, respectively~~. ~~Whereas~~ However the $CSPG_{DFIR}$ caught 1.0% less rainfall than the $CSPG_{PIT}$ (Table 3, Fig.2). These ~~C~~comparative ~~studies~~ results indicate that $CSPG_{PIT}$ catches more rainfall and total precipitation~~*P*~~ compared to the $CSPG_{DFIR}$ and other gauges at the experimental site~~than the $CSPG_{DFIR}$ or the other gauges at the experiment site~~ (Table 3, Fig.2).

3.2.2 ~~Precipitation gauge intercomparison for mixed~~ Mixed precipitation

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

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

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

~~**Fig.3 about here**~~

3.2.3 ~~Precipitation gauge intercomparison for s~~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). During the period fFrom September 2012 to April 2015, the CSPG$_{SA}$, CSPG$_{PIT}$ and CSPG$_{DIFR}$ caught 11.1%, 16.0% and 20.6% more snowfall, respectively, than the CSPG$_{UN}$, respectively. T and the CSPG$_{PIT}$ and the CSPG$_{DFIR}$ caught more 4.4% and 8.5% snowfall , respectively, 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$_{DFIR}$=1.029CSPG$_{PIT}$, R^2=0.994). Although the CSPG$_{DFIR}$ caught 3.9% more snowfall than compared to the CSPG$_{PIT}$ (Table 3), the difference of in total snowfall (43 events) between the CSPG$_{DFIR}$ and the CSPG$_{PIT}$ was only about 3.4 mm (Table 3). Their linear correlation was very significant with a R^2 value of 0.994 (Fig.4f). Blowing snow and thick snow cover have traditionally limited the pit's use as a reference shield for snowfall and mixed precipitation. At the experimental site, blowing snow was rarely observed and the snow cover was usually shallow. This suggests that the CSPG$_{PIT}$ could be used as the a reference gauge for snow precipitation events at the experimental site.

Fig.4 about here

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

3.3 3.4 Catch ratio vs. wind speed

Previous studies showed have shown 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 the 10 m height, so the CSPG$_{UN}$ and the CSPG$_{SA}$ adjustment equations for a single precipitation event are were established obtained with for 10 m height wind speeds during the period of precipitation. On the daily scale, the adjustment equations similar to Eqs.(2)-(4) are were also established obtained, based on the daily mean wind speed converted to thedata at gauge height (0.7m for the CSPGsfor the CSPG, it is 0.7m.) and air temperature data.

To minimize ratio scatter ~~of~~for ~~among~~ the 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). However, ~~I~~in the Hulu watershed, most snowfall and mixed precipitation events ~~are~~ were less than 3.0 mm,~~.~~ ~~For this reason~~thus the limit was reduced and~~,~~ single or daily snowfall and mixed precipitation greater than 1.0 mm ~~was~~were ~~chosen to use in this chapter~~ selected~~.~~, ~~Whereas~~while ~~for the~~ rainfall~~, precipitation~~ events greater than 3.0 mm ~~was~~ were selected. The numbers of ~~the chosen~~ selected precipitation events are shown in Table 4. The CR vs. wind speed relationships for different precipitation types were simulated using cubic polynomials and exponential functions and were~~The catch ratio vs. wind speed relations of different precipitation types are~~ summarized in Table 4 ~~too~~. The $CR_{UN/DFIR}$ and $CR_{SA/DFIR}$ vs. wind speed are statistically significant, but the ~~As shown in Table 4, all the~~ $CR_{PIT/DFIR}$ vs. $W_{s0.7}$ or W_{s10} relationships do not pass the F-test ~~when~~with α=0.10. This phenomenon indicates that both PIT and DFIR are effective in preventing wind from influencing the gauge catch of precipitation, therefore the $CR_{PIT/DFIR}$ is not related to wind speed. ~~Therefore, only $CR_{UN/DFIR}$ and $CR_{SA/DFIR}$ vs. wind speed relations are discussed in the following text.~~

Table 4 about here

~~3.4.1 Rainfall catch ratio vs. wind speed~~

Fig.5 presents scatter plots ~~of~~ for the $CR_{UN/DFIR}$ or $CR_{SA/DFIR}$ vs. wind speed for rainfall. The CRs vary from 80% to 110%. With increasing wind speed, the CRs decrease~~d~~ slightly. Only ~~The following two equations~~ Eq. (10) ~~and (11)~~ shown in Fig.5 and Table 4 could be used to adjust the rainfall event data from the ~~$CSPG_{UN}$ and~~ $CSPG_{SA}$~~, respectively~~. ~~They both pass the F-test when α<0.1 (Table 4).~~ It is significant at 0.03 level (Table 4). As described in section 2.2, the Eq.(10) was fitted using NONLINEAR function in SPSS software (Analyze\Regression\Nonlinear). The F-value was then calculated by using regression and residual sum of squares from SPSS (Snedecor and Cochran, 1989). Based on the F-value and degree of freedom (Df), the significant level (α) was obtained by using the FDIST function in Microsoft Excel. –Other forms such as the exponential expression were treated in a similar way.

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

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

~~Where~~ where ~~$CR_{UN/DFIR,Rain}$ and~~ $CR_{SA/DFIR,Rain}$ is the rainfall catch ratio (%) per observation of ~~the $CSPG_{UN}$ and~~ the

$CSPG_{SA}$~~, respectively,~~ and W_{s10} is the wind speed at 10m ~~height~~ during ~~the~~ rainfall period ~~of rainfall~~ (m s^{-1}).

Fig.5 about here

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

~~3.4.2 Mixed precipitation catch ratio vs. wind speed~~

For the mixed precipitation events, the $CR_{UN/DFIR,Mixed}$ ~~and $CR_{SA/DFIR,Mixed}$~~ vs. W_{s10} ~~relations~~ relationships are exponential (Table 4, Fig.6). The CRs vary ~~largely~~ greatly from about 60% to 120%. For the $CSPG_{UN}$, the exponential relationship Eq. (~~12~~11) passes the F-test ~~when~~with α~~<0.10~~=0.07, whereas for the $CSPG_{SA}$, the Eq.(~~13~~12) ~~doesn't pass but has a~~ α value ~~of~~ is about 0.16 (Table 4).

Fig.6 about here

$$CR_{UN/DFIR,Mixed} = 100e^{-0.06W_{s10}} \qquad 0<W_{s10}<5.9 \qquad (~~12~~11)$$

$$CR_{SA/DFIR,Mixed} = 100e^{-0.04W_{s10}} \qquad 0<W_{s10}<5.9 \qquad (~~13~~12)$$

On the daily scale, the ~~best~~ relationships between mixed precipitation CR and wind speed at gauge height ($W_{s0.7}$) are also exponential ~~power law~~ expressions (Table 4, Fig.6). Similarly, for the $CSPG_{UN}$, Eq. (~~14~~13) passes the F-test ~~when~~with α<0.10, whereas the Eq.(~~15~~14) with an α value of about 0.~~12~~ 18 doesn't (Table 4).

$$CR_{UN/DFIR,Mixed} = 100e^{-0.12W_{s0.7}} \qquad 0<W_{s0.7}<2.9 \qquad (~~14~~13)$$

$$CR_{SA/DFIR,Mixed} = 100e^{-0.07W_{s0.7}} \qquad 0<W_{s0.7}<2.9 \qquad (~~15~~14)$$

From Eq. (3), air temperature may also affect the mixed precipitation CRs on the daily scale. Eqs. (~~16~~15)-(1~~7~~6) are ~~established~~ obtained as follows. However, these two new equations ~~don't~~ do not pass the F-test ~~when~~with ~~α=~~α<0.20.

$$CR_{UN/DFIR,Mixed} = 13.83W_{s0.7}^{-4.91} + 1.25T_{max} - 0.88T_{min} + 62.21 \qquad α=0.20 \qquad (~~16~~15)$$

$$CR_{SA/DFIR,Mixed} = 10.74W_{s0.7}^{-4.74} + 0.85T_{max} - 0.18T_{min} + 76.20 \qquad α=0.29 \qquad (~~17~~16)$$

~~Where~~ where T_{max} and T_{min} ~~is~~ are 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} relationships are ~~evident~~ significant (Table 4, Fig.7). For the $CSPG_{UN}$, the exponential relationship Eq.(~~18~~17) passes the F-test ~~when~~with α<0.001.

~~The~~ Eq.(~~18~~17) is similar ~~with~~ to ~~the~~ Eq.(5) suggested by Yang et al. (1991). For the $CSPG_{SA}$, its exponential expression in Eq.(18)~~the power law expression Eq.(19)~~ passes the F-test ~~when~~ with α~~<0.05~~=0.07 (Table 4).

Fig.7 about here

$$CR_{UN/DFIR,Snow} = 100e^{-0.08W_{s10}} \qquad 0<W_{s10}<4.8 \qquad (\sout{18}17)$$

$$CR_{SA/DFIR,Snow} = 100e^{-0.02W_{s10}} \qquad 0<W_{s10}<4.8 \qquad (\sout{19}18)$$

On daily scale, the relationships between snowfall CRs and wind speed at gauge height ($W_{s0.7}$) are also exponential expressions (Table 4, Fig.7). ~~f~~For the $CSPG_{UN}$ and ~~the~~ $CSPG_{SA}$, the Eqs. (~~20~~19) ~~and Eq.~~ (~~21~~20) pass the F-test ~~when~~with α<0.001 and α~~<0.10~~=0.14, respectively (Table 4). Eqs. (~~18~~17) - (~~21~~19) could therefore be directly used to calibrate the wind-induced snowfall measurement errors for $CSPG_{UN}$ and ~~the~~ $CSPG_{SA}$.

$$CR_{UN/DFIR,Snow} = 100e^{-0.11W_{s0.7}} \qquad 0<W_{s0.7}<3.1 \qquad (\sout{20}19)$$

$$CR_{SA/DFIR,Snow} = 100e^{-0.03W_{s0.7}} \qquad 0<W_{s0.7}<3.1 \qquad (20\sout{21})$$

Air temperature may also affect the snowfall CR~~s~~ on the daily scale as shown in Eq.(2). Eqs. (~~22~~21)~~-~~-(~~23~~22) are the new equations ~~associating~~ associated with daily maximum air temperature. However, these two new equations are no~~t~~ better than Eqs. (~~20~~19)-(~~21~~20) according to their ~~α value of~~ F-test α values.

$$CR_{UN/DFIR,Snow} = 42.29W_{s0.7}^{-1.06} - 1.06T_{max} + 55.91 \qquad α=4.2E\text{-}5 \qquad (\sout{22}21)$$

$$CR_{SA/DFIR,Snow} = -9.46\ln(W_{s0.7}) - 0.31T_{max} + 98.76 \qquad α=0.17 \qquad (\sout{23}22)$$

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

4 Discussion

4.1 Comparison with other studies

Yang et al. (1991) carried out a precipitation intercomparison experiment from 1985 to 1987 ~~in~~ at the ~~valley~~ Tianshan site~~e of Tianshan~~. Their results indicated that the ~~ratios of~~ $CSPG_{DFIR}/CSPG_{UN}$ ratios for snowfall and mixed precipitation were 1.222 and 1.160, respectively. In the Hulu watershed, the~~se~~se ratios ~~of $CSPG_{DFIR}/CSPG_{UN}$ for snowfall and mixed precipitation~~ were 1.165 (Fig.4c) and 1.072 (Fig.3c), ~~and the~~while those ~~ratios of~~ for

CSPG$_{PIT}$/CSPG$_{UN}$ f~~or snowfall and mixed precipitation~~ were 1.162 (Fig.4b) and 1.082 (Fig.3b), respectively. Similar topographic features and shading induced similar lower wind speeds and led to similar catch ratios at both sites~~, which led to the similar catch ratios~~. For the Tianshan reference site, wind speed (W_{s10}) on rainfall or snowfall days never exceeds 6 m s^{-1} and 88% of the ~~yearly~~ total annual precipitation took place with wind speeds below 3 m s^{-1}. ~~For~~ At the Hulu watershed site, daily mean wind speeds (W_{s}~~0.7~~$_{10}$) on precipitation days never exceeded ~~3.5~~6.4 m s^{-1}, and over ~~98.9~~55.2% of the precipitation events occurred ~~when~~ with daily mean wind speeds ~~were~~ below 3 m s^{-1}. During the period of precipitation, the largest wind speed at 10 m height is about 8.8 m s^{-1}, and over 54.2% of the precipitation events occurred ~~when~~ with wind speeds ~~were~~ below 3 m s^{-1}.

As Ren et al. (2003) reported, across 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 compared to the CSPG$_{UN}$. Large wind-induced differences were often observed at the mountainous western stations and in north-eastern China. At the Gangcha station (100°08′, 37°20′, 3015 m), which also lies in the Qilian Mountains at a similar elevation about 200 km 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$_{PIT}$ captured 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 that reported by Ren et al. (2003) due to differences in the wind regime. At the Gangcha station, daily mean wind speeds (W_{s10}) on precipitation days during the experimental period from 1992 to 1998 never exceeded 8.5 m s^{-1}, and over 35.1% of the precipitation events occurred with daily mean wind speeds below 3 m s^{-1}. The average daily mean W_{s10} was about 3.4 m s^{-1} on precipitation days from 1992 to 1998 at the Gangcha station, whereas at the Hulu watershed site from 2010 to 2015, the average value was about 2.9 m s^{-1} on precipitation days.

As Ren et al. (2003) reported, across~~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~~ compared to the CSPG$_{UN}$. Large wind-induced differences ~~are~~ were often observed at the ~~western~~ mountainous western stations and in ~~the Northeastern~~ north-eastern China. At the Gangcha station (100°08′, 37°20′, 3015 m) , which also lies in the Qilian Mountains ~~with~~ at a similar elevation~~s 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~~ captured 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 that reported by ~~the~~ Ren et al. (2003) ~~presented~~ reported due to differences in the wind regime~~due to the~~

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

4.2 CSPG$_{PIT}$ as a reference for solid precipitation

The pit ~~shield~~ is the WMO reference configuration for liquid precipitation measurements and the DFIR is the reference configuration for solid precipitation measurements (Sevruk et al., 2009). In this study, the CSPG$_{PIT}$ ~~measures~~ measured more rainfall and mixed precipitation than the CSPG$_{DFIR}$. For the snowfall, the catch ratio for the CSPG$_{PIT}$ ~~is~~ was 0.96, close to ~~the~~that of the~~ ~~CSPG$_{DFIR}$ ~~catch ratio~~measurement. The difference ~~of~~ in total snowfall (43 events) between the CSPG$_{PIT}$ and ~~the~~ CSPG$_{DFIR}$ ~~is~~ was only about 3.4 mm from September 2012 to April 2015 at the Hulu watershed site. The snowfall for autumn and spring was greater than for winter during the observation period at the intercomparison site (Fig.8). The snowfall is wetter in autumn and spring than in winter, and wetter snowfall means less blowing or drifting snow. Thus the CSPG$_{PIT}$ could serve as a reference for liquid and solid precipitation in ~~the~~ environments similar to that of the Hulu watershed site. Precipitation collected by the CSPG$_{PIT}$ would be most affected when blowing or drifting snow occurred, and induced a faulty precipitation value (Goodison et al., 1998; Ren and Li, 2007). Previous studies have ~~indicates~~indicated, however, that for most of China the maximum snow depth~~s~~ in the past 30 years ~~have~~ has been less than 20 cm (Li, 1999), ~~and~~ with average snow depths ~~were less than~~below 3 cm (Li et al., 2008; Che et al., 2008). Fig.~~8~~ 9 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~~ middle and south-western Tibetan Plateau, northern Xinjiang province and north-eastern China. Statistical analysis indicates that for more than 94% of stations, solid precipitation comprises~~is~~ less than 15% of the annual precipitation ~~amount~~. Ren ~~and Li~~et al. (~~2007~~2003) ~~has~~ reported, that among the ~~29276~~ 2286 ~~precipitation~~ snowfall events, ~~there are~~ only ~~784~~ 54 were blowing or drifting snow events accounting ~~to~~ for about ~~2.7~~2.4% ~~at the~~for ~~30~~ 26 stations ~~over~~ across China. Based on the regionalization of snow drift in China, ~~These~~ blowing or drifting snow events occur mostly ~~occur in~~ on the central and south-western~~south-eastern~~ Tibetan Plateau, in the northern Xinjiang province and in north-eastern China

(~~Ren et al., 2003~~Wang and Zhang, 1999). In these regions, the $CSPG_{DFIR}$ should be used as a reference gauge. In other regions, the $CSPG_{PIT}$ may be applicable. Based on the CMA snowfall and snow depth data, and the regionalisation of snow drift in China, the applicable regions for the $CSPG_{PIT}$ and $CSPG_{DFIR}$ as reference gauges are shown in Fig.10.~~The applicable regions for the $CSPG_{PIT}$ and the $CSPG_{DFIR}$ as reference gauges are shown in Fig.9 based on CMA snowfall and snow depth data.~~

Fig.8 about here

Fig.9 about here

Fig.10 about here

4.3 ~~Uncertainties~~ Limitations of ~~the~~ this experiment

Although the measurements procedure ~~is~~ were based on the CMA's ~~criterion~~criteria, ~~the~~ manual observation ~~has low frequency~~were infrequent, and as a result, some precipitation events ~~are~~ were summarized as ~~one~~ single events, especially in the evenings. The automatic meteorological tower ~~can~~ could observe precipitation and wind speeds half-hourly ~~precipitation and wind speeds~~ during the precipitation period, but the $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ ~~are~~ were observed only twice per day. In this field experiment, the precipitation phase ~~is~~ were also discriminated by the observers. This method is somewhat ~~rough~~ imprecise although ~~it~~ this has ~~been~~ remaned the ~~standard~~ traditional ~~way~~ method since the 1950s at the CMA stations (CMA, 2007b).

The ~~used~~ wind speeds at gauge height and ~~at~~ the 10 m height ~~are~~ were not observed directly~~,~~ but ~~they are~~rather calculated from the observed data at 1.5 m and 2.5m heights according to the Monin-Obukhov theory and the gradient method (Eq~~s~~. (~~9~~8)). Although this method is widely used, it is effective only under neutral atmospheric conditions. ~~During~~ For the precipitation period from September 2012 to April 2015, the Z_0 ~~is~~ was calculated using Eq. (9). The results showed the Z_0 to be about 0.06 m ~~of the~~on average but it ~~varies~~ varied from near zero to 0.67 m. As shown in Fig.~~10~~11, in about 68.9% and 95.1% of instances, the Z_0 ~~is~~ was lower than 0.05 m and 0.25 m, respectively. In rare cases when the Z_0 was very large, as shown in Fig.11, the Z_0 was arbitrarily assigned 1/2 of the grass height (h) at the site based on the equation Z_0=0.5hL_e provided by Lettau (1969). The very large Z_0 values usually appeared in late August and early September when the vegetation coverage (L_e) was close to 100% at the Hulu watershed site.~~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~~ 11 about here

5 Conclusions

The present experimental field study focused on wind-induced bias in precipitation measurements by CSPGs specifically in a high mountain environment. ~~–~~The precipitation intercomparsion experiment in the Hulu watershed of the Qilian Mountains ~~indicates~~ indicated that the CSPG$_{PIT}$ ~~catches~~ caught more rainfall, mixed precipitation and total precipitation but less snowfall than the CSPG$_{DFIR}$. From most to ~~the~~ least rainfall and mixed precipitation measured, ~~it can be ordered as follows~~their ranking ~~:~~was CSPG$_{PIT}$ > CSPG$_{DFIR}$ > CSPG$_{SA}$ > CSPG$_{UN}$~~.~~, ~~While~~ whereas in the snowy season, ~~it follows the rule that~~ better wind~~-~~ shielding increased ~~catch with more~~ the snow catch~~, and they can be ordered:~~ ~~–~~leading to CSPG$_{DFIR}$ > CSPG$_{PIT}$ > CSPG$_{SA}$ > CSPG$_{UN}$. ~~The wind-induced bias of CSPG$_{SA}$ and the CSPG$_{UN}$ are well tested, and the most adjustment equations could be used. They would help to improve the precipitation accuracy in China.~~

In the regions with~~–~~ ~~little~~lower snowfall, such as the south and central part of China (Zhang and Zhong, 2014), and ~~the~~ in regions with a similar climate and environment to that of the Hulu watershed site, the CSPG$_{PIT}$ could be used as ~~the~~ a reference gauge ~~considering~~ because of its highest catch ratio, simplicity ~~and low cost~~ and lower maintenance requirements. In north-eastern China, northern Xinjiang province and ~~southeastern~~ central and south-western Tibetan Plateau where snowfall often occurs, the best choice ~~for~~ of reference gauge would be the CSPG$_{PIT}$ for rainfall and CSPG$_{DFIR}$ for snowfall observations.

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

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

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

Element	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
Monthly precipitation (mm)	3.5	2.5	11.0	8.8	67.7	69.6	87.1	111.6	57.7	24.0	2.7	1.0	447.2
Monthly mean air temperature (°C)	-12.4	-7.7	-4.4	2.2	7.0	11.2	12.5	12.1	8.0	1.4	-5.6	-11.3	1.1
Monthly mean daily maximum air temperature (°C)	-4.0	0.7	3.5	10.3	14.3	18.2	19.5	19.7	15.4	10.2	3.6	--1.9	9.1
Monthly mean daily minimum air temperature (°C)	-19.0	-14.8	-11.6	-5.2	0.6	4.9	6.8	5.8	1.8	-5.5	-12.7	-18.2	-5.6
Monthly mean wind speed at the 1.5m height (m s^{-1})	1.79	1.96	2.30	2.55	2.42	1.98	1.82	1.81	1.93	1.81	2.08	1.96	2.03
Monthly mean wind speed at the 2.5m height (m s^{-1})	1.79	2.02	2.43	2.77	2.65	2.16	2.04	2.02	2.16	1.99	2.19	2.01	2.18
Monthly potential evaporation (mm)	31.6	47.0	79.4	124.4	140.9	155.0	141.7	127.0	101.6	75.2	47.3	31.0	1102.2

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

Table 2. The precipitation measurement intercomparison experiment in the Qilian mountainsMountains.

Gauge	Abbreviation	Size(φ stand fordenotes orifice diameter and h foris observation height)	Start date	End date	Measure Observation time
An uUnshielded China standard precipitation gauge (CMA, 2007a)	$CSPG_{UN}$	φ=20cm, h=70cm	Jun 2009	Apr, 2015	20:00 and 08:00, LTLocal time
Single Alter shield (Struzer, 1971) around a CSPG	$CSPG_{SA}$	φ=20cm, h=70cm	Jun 2009	Apr, 2015	20:00 and 08:00, LTLocal time
A CSPG in a Pit (Sevruk and Hamon, 1984)	$CSPG_{PIT}$	φ=20cm, h=0cm	Sep 2010	Apr, 2015	20:00 and 08:00, LTLocal

					time
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~~Local time

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 relationships at the Hulu watershed intercomparison site, 2012-2015.

Temporal scale	Phase	Gauges	~~Best c~~Catch ratio (CR) vs. wind speed relationships*	*P* (mm)	No. of events	F-test
Precipitation event	Rain	$CSPG_{UN}$	$CR_{UN/DFIR,Rain}=0.181W_{s10}^3-0.256W_{s10}^2-0.795W_{s10}+100$ R^2=0.~~070~~042	*P*>3.0	103	α=0.~~06~~23
		$CSPG_{SA}$	$CR_{SA/DFIR,Rain}=0.188W_{s10}^3-0.719W_{s10}^2+0.551W_{s10}+100$ R^2=0.~~099~~083			α=0.~~01~~03
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Rain}=0.150W_{s10}^3-0.425W_{s10}^2+1.119W_{s10}+100$ R^2=0.~~023~~008			α=0.~~50~~83
	Mixed	$CSPG_{UN}$	$CR_{UN/DFIR,Mixed}=100e^{-0.06W_{s10}}$ R^2=0.~~198~~194	*P*>1.0	24	α=0.07
		$CSPG_{SA}$	$CR_{SA/DFIR,Mixed}=100e^{-0.04W_{s10}}$ R^2=0.~~102~~100			α=0.16
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Mixed}=100e^{-7E-0W_{s10}}$ R^2=0.~~023~~000			α=~~0.47~~no data
	Snow	$CSPG_{UN}$	$CR_{UN/DFIR,Snow}=100e^{-0.08W_{s10}}$ R^2=0.~~420~~412	*P*>1.0	~~32~~34	α=~~4.7~~6.4E-05
		$CSPG_{SA}$	$CR_{SA/DFIR,Snow}=100W_{s10}^{-0.02}$ R^2=0.~~122~~090			α=0.~~04~~07
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Snow}=100e^{-0.01W_{s10}}$ R^2=0.~~110~~024			α=0.~~30~~35
Daily precipitation	Rain	$CSPG_{UN}$	$CR_{UN/DFIR,Rain}=-1.400W_{s0.7}^3+2.987W_{s0.7}^2-6.116W_{s0.7}+100$ R^2=0.~~045~~032	*P*>3.0	90	α=0.~~26~~37
		$CSPG_{SA}$	$CR_{SA/DFIR,Rain}=-0.924W_{s0.7}^3+1.158W_{s0.7}^2-3.338W_{s0.7}+100$ R^2=0.~~031~~021			α=0.~~43~~55
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Rain}=-0.952W_{s0.7}^3-1.503W_{s0.7}^2+2.237W_{s0.7}+100$ R^2=~~0.017~~ 0.00			α=~~0.68~~no data
	Mixed	$CSPG_{UN}$	$CR_{UN/DFIR,Mixed}=100e^{-0.12W_{s0.7}}$ R^2=0.~~169~~144	*P*>1.0	21	α=0.0~~9~~6
		$CSPG_{SA}$	$CR_{SA/DFIR,Mixed}=100e^{-0.07W_{s0.7}}$ R^2=0.~~122~~094			α=0.~~12~~18
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Mixed}=100e^{-0.001W_{s0.7}}$ R^2=0.~~017~~003			α=~~0.60~~no data
	Snow	$CSPG_{UN}$	$CR_{UN/DFIR,Snow}=100e^{-0.11W_{s0.7}}$ R^2=0.~~577~~477	*P*>1.0	27	α=~~5.7~~1.8E-~~6~~04
		$CSPG_{SA}$	$CR_{SA/DFIR,Snow}=100e^{-0.03W_{s0.7}}$ R^2=0.~~111~~087			α=0.~~09~~14
		$CSPG_{PIT}$	$CR_{PIT/DFIR,Snow}=100e^{-0.01W_{s0.7}}$ R^2=~~0.134~~ 0.00			α=~~0.33~~no data

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

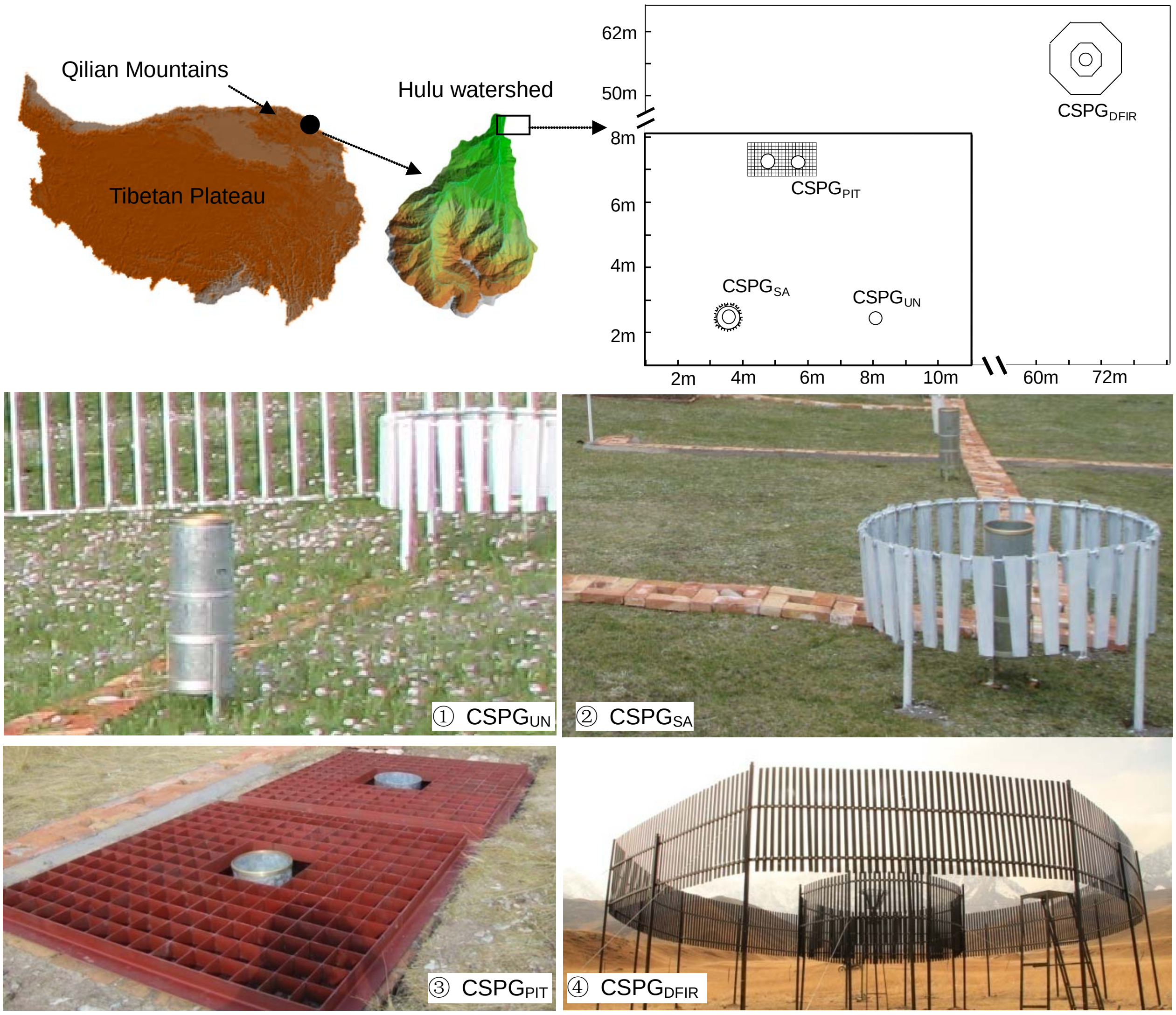

Figure 1. Precipitation gauge intercomparison experiment in the Qilian ~~mountains~~Mountains, Tibetan Plateau.

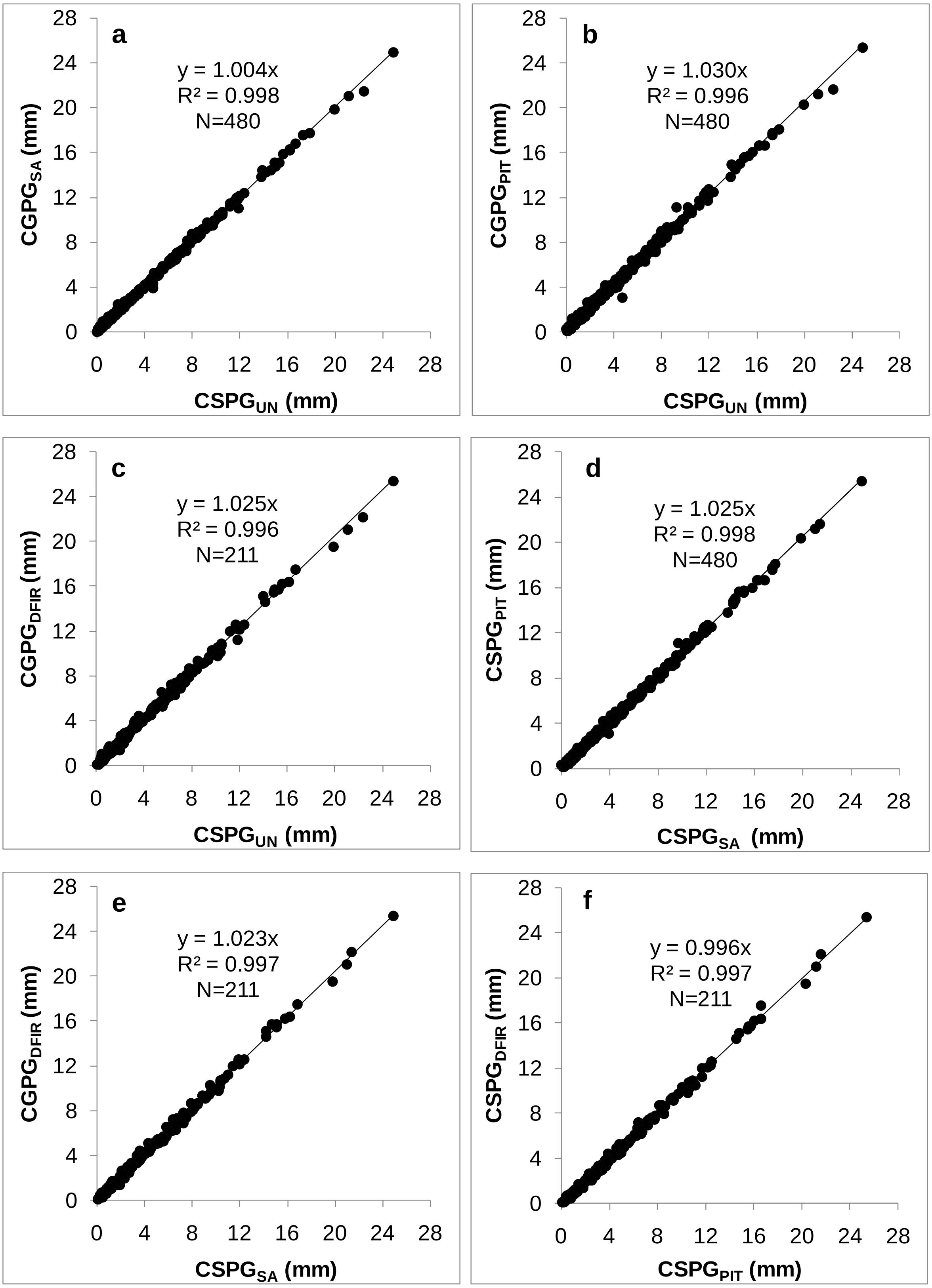

Figure 2. Intercomparison plots among CSPG$_{UN}$, CSPG$_{SA}$, CSPG$_{PIT}$ and CSPG$_{DFIR}$ for the rainfall events from September 2010 (**a**, **b** and **d**) ~~or~~ and September 2012 (**c**, **e** and **f**) to April 2015**.**

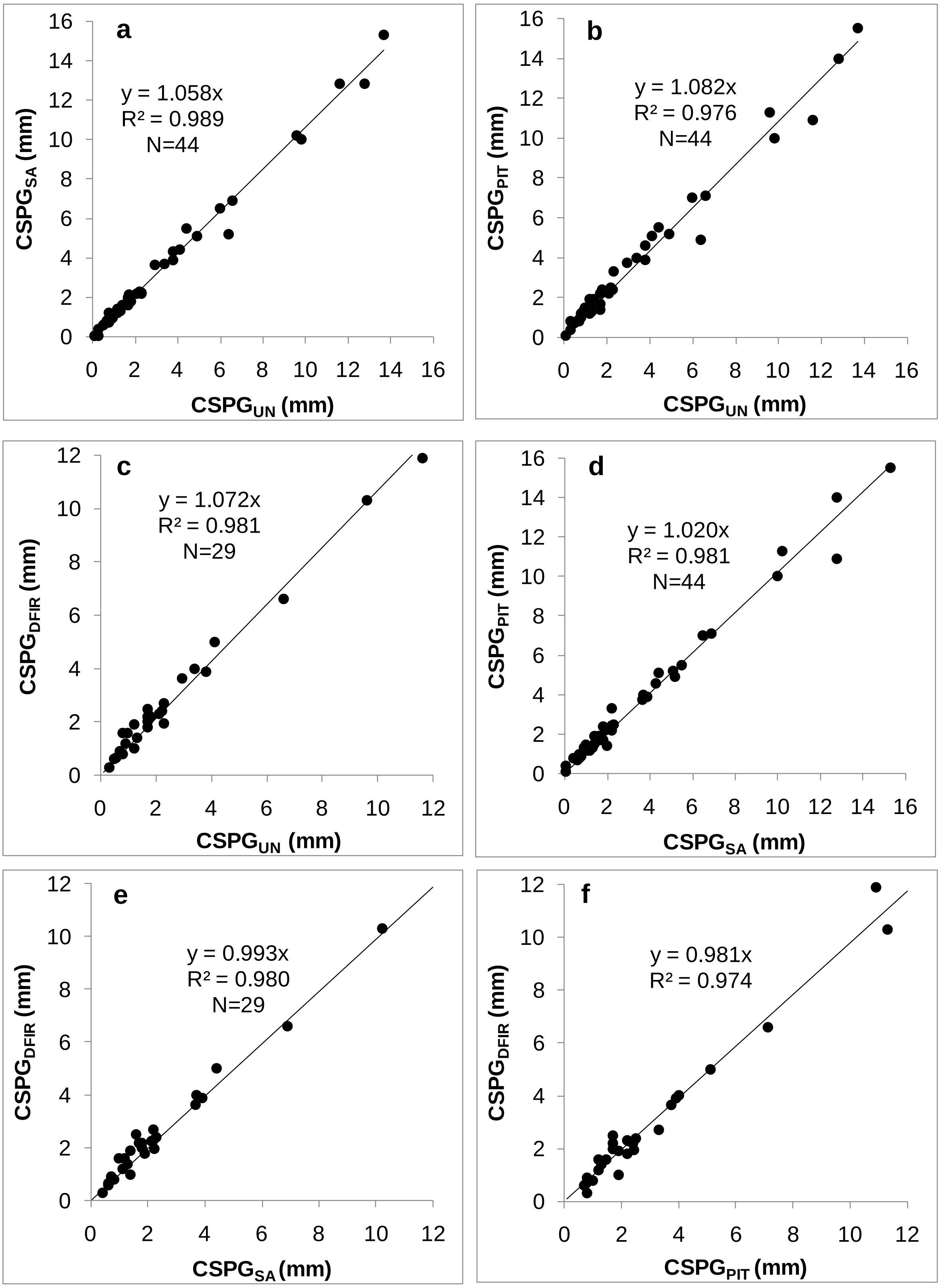

Figure 3. Intercomparison plots among $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ for the mixed precipitation events from September 2010 (**a**, **b** and **d**) ~~or~~ and September 2012 (**c**, **e** and **f**) to April 2015**.**

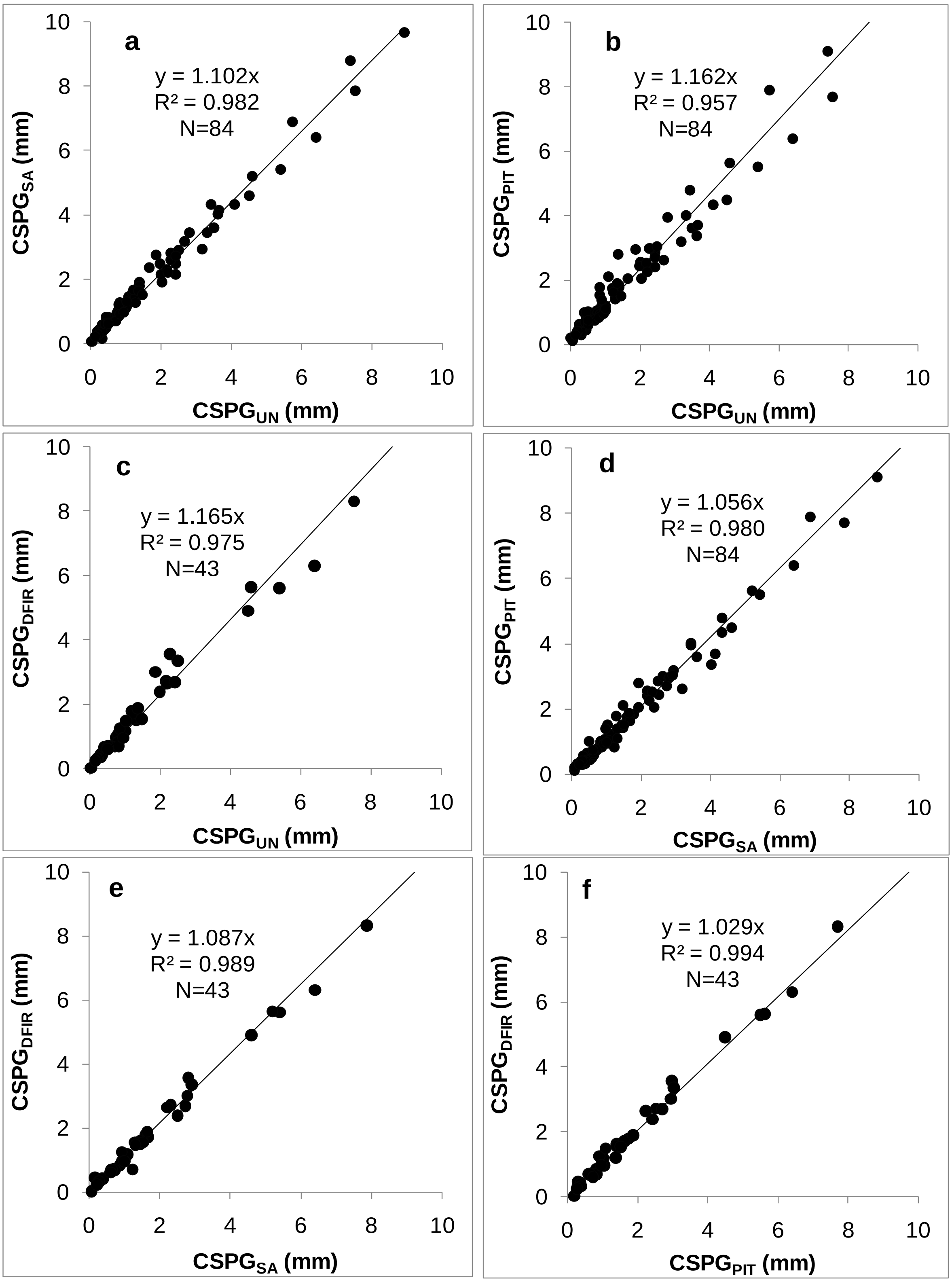

Figure 4. Intercomparison plots among $CSPG_{UN}$, $CSPG_{SA}$, $CSPG_{PIT}$ and $CSPG_{DFIR}$ for the snowfall events from September 2010 (**a**, **b** and **d**) ~~or~~ and September 2012 (**c**, **e** and **f**) to April 2015**.**

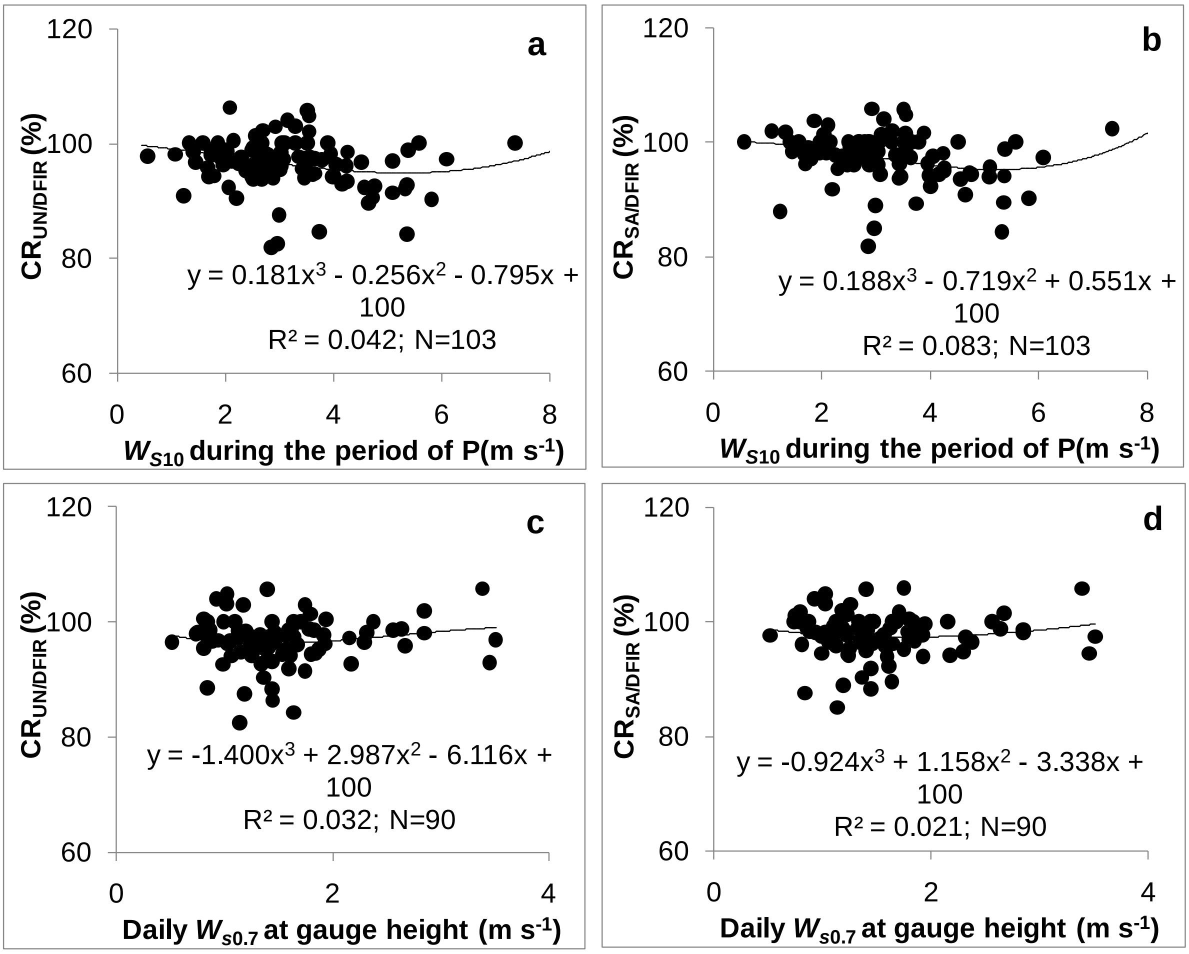

Figure 5. Catch ratios (CRs) vs. wind speed for the rainfall events (**a** and **b**) and the daily rainfall (**c** and **d**) greater than 3.0 mm.

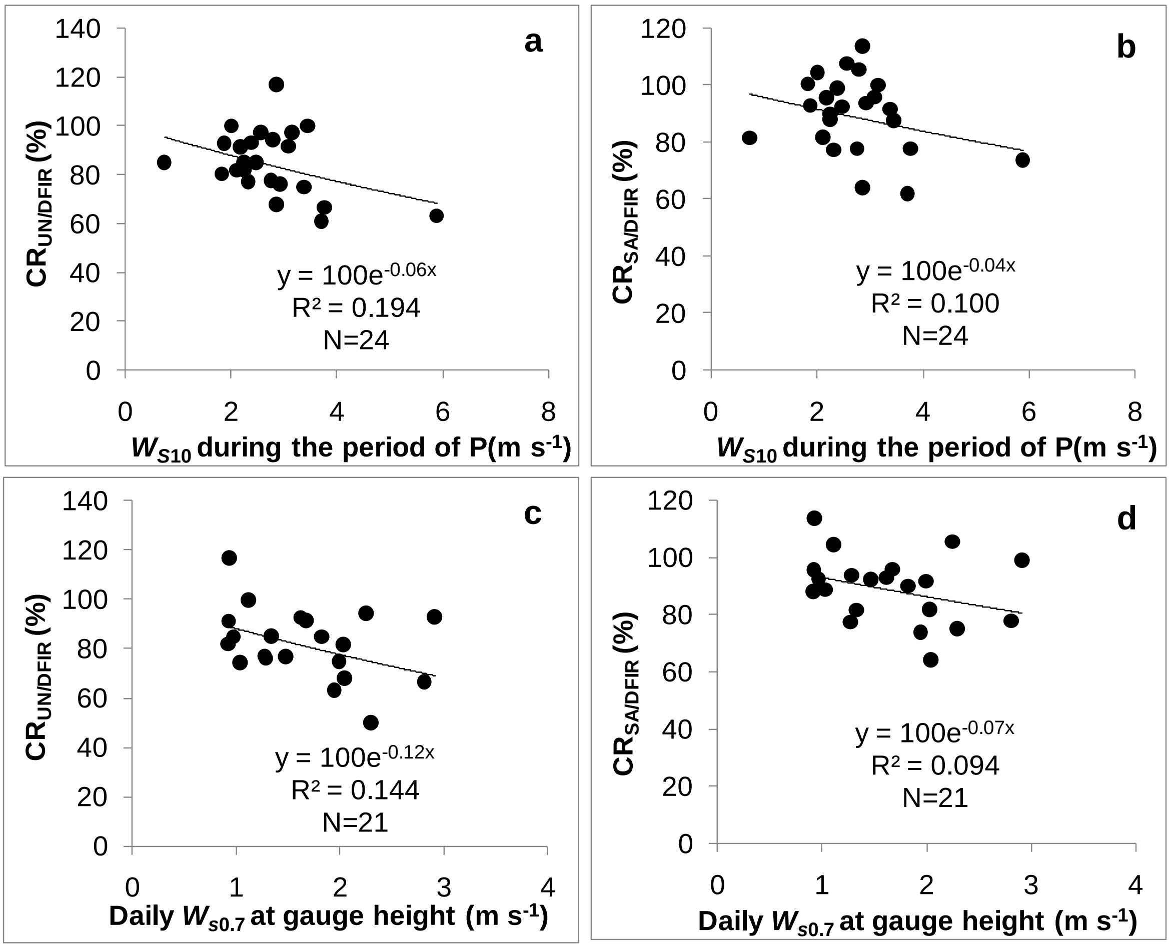

Figure 6. Catch ratios (CRs) vs. wind speed for the mixed precipitation events (**a** and **b**) and the daily mixed precipitation (**c** and **d**) greater than 1.0 mm.

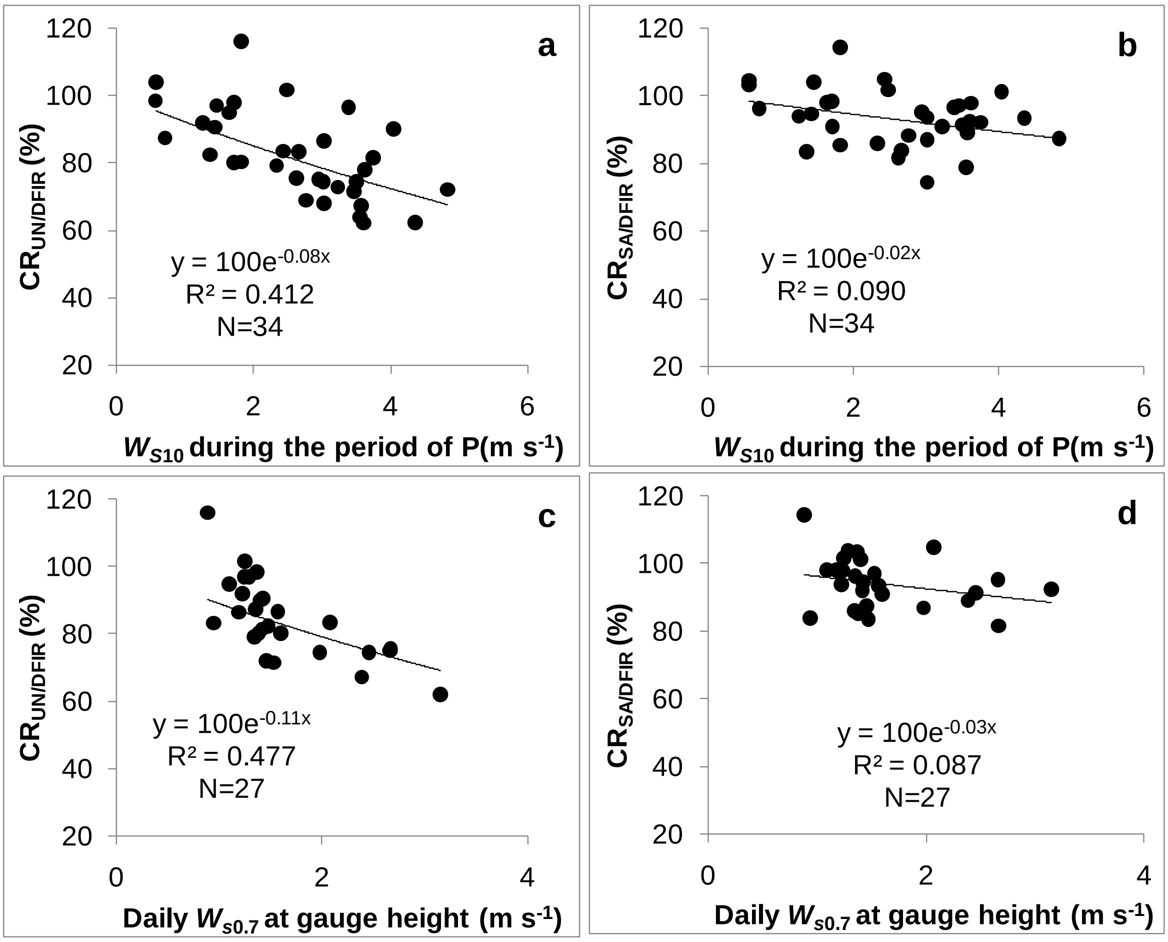

Figure 7. Catch ratios (CRs) vs. wind speed for the snowfall event (**a** and **b**) and the daily (**c** and **d**) snowfall greater than 1.0 mm.

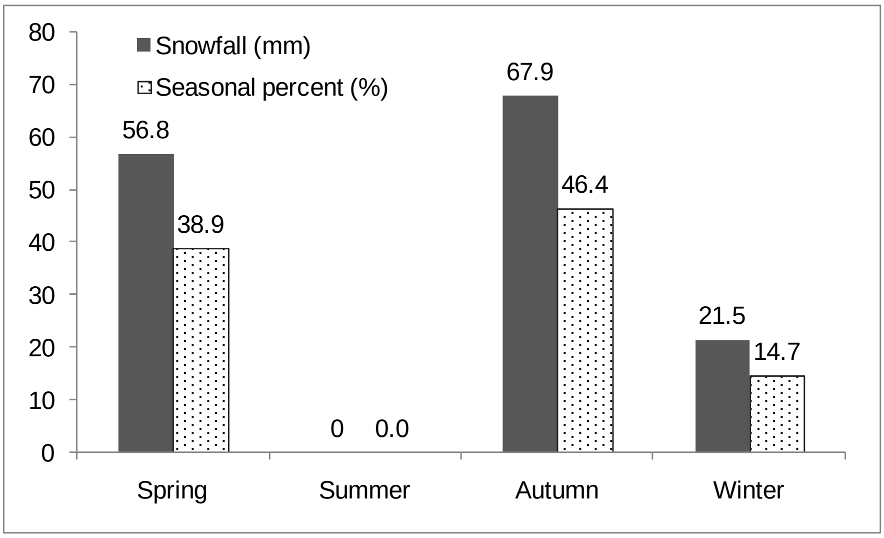

Figure 8. Seasonal snowfall and its percentage from September 2010 to April 2015 at the Hulu watershed site.

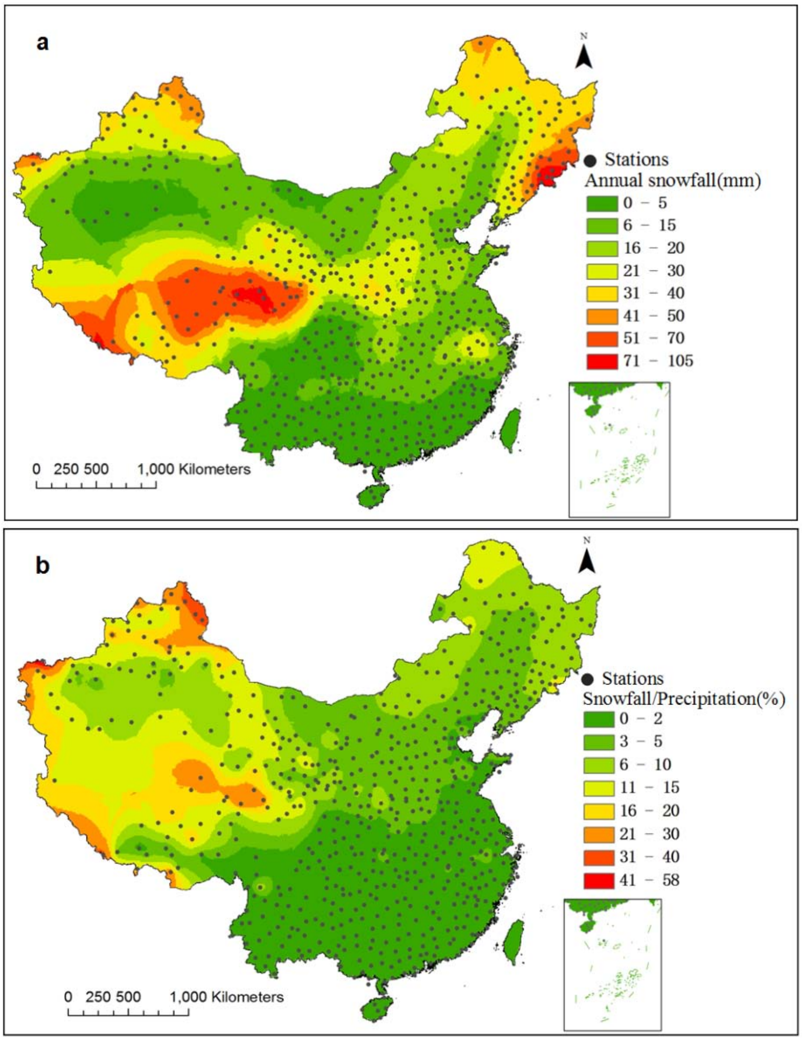

Figure 89. (**a**) Annual snowfall (mm) and (**b**) ratio of annual snowfall proportion (annual snowfall/annual precipitation)to total precipitation in China.

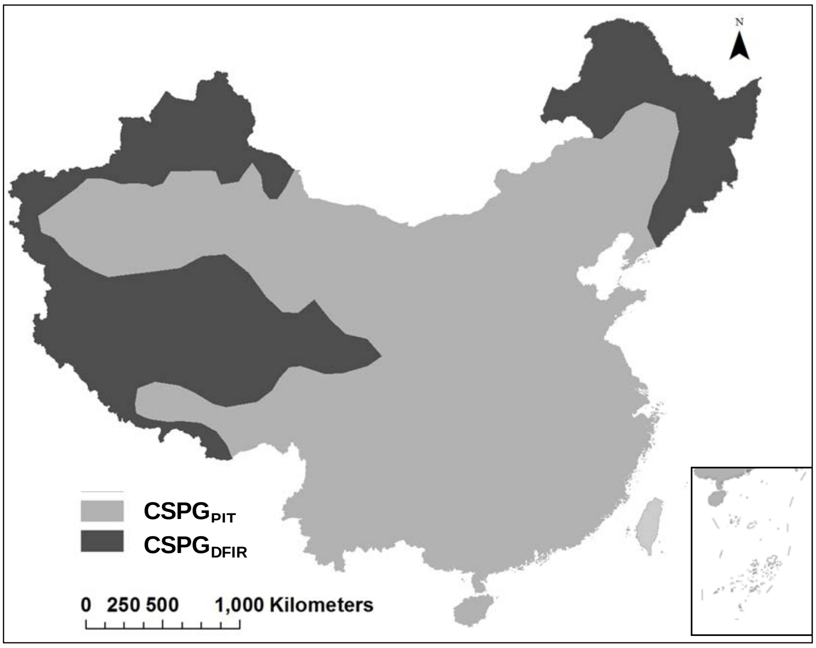

Figure ~~9~~10. Applicable regions in China for the $CSPG_{PIT}$ and ~~the~~ $CSPG_{DFIR}$ as reference gauges ~~in China~~.

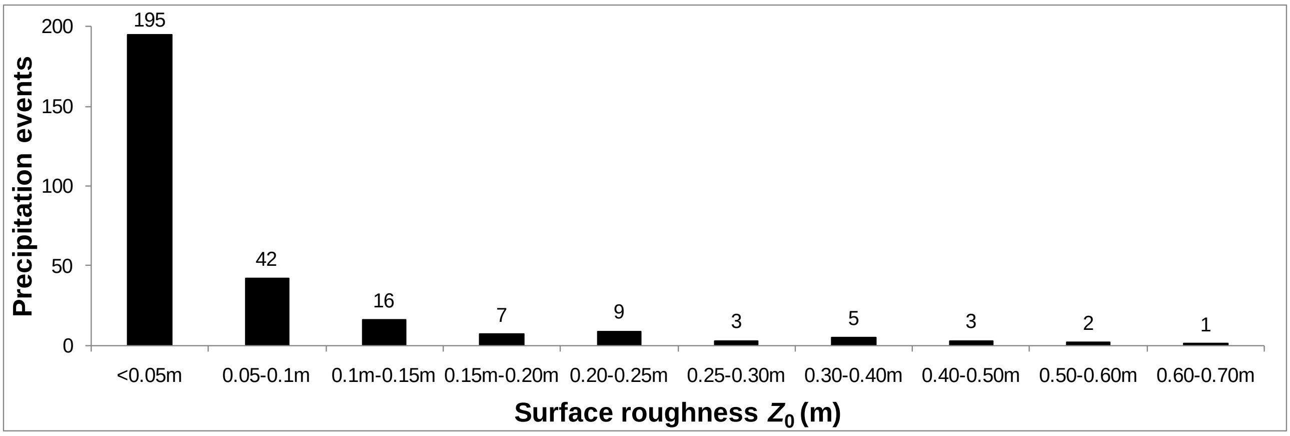

Figure ~~10~~11. ~~The s~~Surface roughness during the precipitation period from September 2012 to April 2015.