(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 0.5\ln(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_{s10}^3 and W_{s10}^2 should be converted into new variables X_1= W_{s10}^3 and X_2= W_{s10}^2 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$_{\text{PIT}}$ 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\textsubscript{PIT} and the CSPG\textsubscript{DFIR} caught more 3.6\% and 2.5\% rainfall,

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

Author's changes in manuscript: No revision.

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,.....

2. Page 3 Line 6-7: 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: 3. Page 3 Line 13: (2007) had conducted an intercomparison experiment at 39 sites (altitude varies from about 4.8 m to 3857 m) over China, and they used 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

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

<table>
<thead>
<tr>
<th>ID</th>
<th>Country</th>
<th>Gauge type</th>
<th>Setting orifice height (cm)</th>
<th>Area of orifice (cm²)</th>
<th>Number of selected weather station</th>
<th>Wind-induced error correction procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Bangladesh</td>
<td>U.S. 8&quot;</td>
<td>70</td>
<td>324</td>
<td>1</td>
<td>Yang et al. (1998)</td>
</tr>
<tr>
<td>II</td>
<td>China</td>
<td>CSPG</td>
<td>70</td>
<td>314</td>
<td>152</td>
<td>Yang (1988) and Yang et al. (1991)</td>
</tr>
<tr>
<td>III</td>
<td>India</td>
<td>Indian</td>
<td>30</td>
<td>200</td>
<td>22</td>
<td>No bias-correction result can be refereed, dealt by procedure of Tretyakov due to similar size</td>
</tr>
<tr>
<td>IV</td>
<td>Kazakhstan</td>
<td>Tretyakov</td>
<td>40</td>
<td>200</td>
<td>9</td>
<td>Goodison et al. (1998)</td>
</tr>
<tr>
<td>V</td>
<td>Kyrgyzstan</td>
<td>Tretyakov</td>
<td>40</td>
<td>200</td>
<td>7</td>
<td>Goodison et al. (1998)</td>
</tr>
<tr>
<td>VI</td>
<td>Nepal</td>
<td>Nepal2003</td>
<td>100</td>
<td>324</td>
<td>3</td>
<td>No bias-correction result can be refereed, dealt by procedure of U.S. 8&quot; due to similar size</td>
</tr>
<tr>
<td>VII</td>
<td>Pakistan</td>
<td>MK2</td>
<td>30</td>
<td>127</td>
<td>21</td>
<td>Essery and Wilcock (1991)</td>
</tr>
<tr>
<td>VIII</td>
<td>Tajikistan</td>
<td>Tretyakov</td>
<td>40</td>
<td>200</td>
<td>9</td>
<td>Goodison et al. (1998)</td>
</tr>
<tr>
<td>IX</td>
<td>Turkmenistan</td>
<td>Tretyakov</td>
<td>40</td>
<td>200</td>
<td>2</td>
<td>Goodison et al. (1998)</td>
</tr>
<tr>
<td>X</td>
<td>Uzbekistan</td>
<td>Tretyakov</td>
<td>40</td>
<td>200</td>
<td>15</td>
<td>Goodison et al. (1998)</td>
</tr>
</tbody>
</table>

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From Sevruk and Klemm (1989):

<table>
<thead>
<tr>
<th>No</th>
<th>Code</th>
<th>Area of orifice $A_0$ [cm²]</th>
<th>Name</th>
<th>Country of origin</th>
<th>Material</th>
<th>Depth of collector [cm]</th>
<th>Height of gauge [cm]</th>
<th>$A_{ag}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>20-22-P</td>
<td>200</td>
<td>Indian</td>
<td>India</td>
<td>fibre glass</td>
<td>22</td>
<td>50</td>
<td>4.9</td>
</tr>
</tbody>
</table>
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: Authors' response: The word 'gauges' is added.

Author's changes in manuscript: One was a comparison of the CSPGUN, CSPGSA, CSPGPIT and CSPGDFIR gauges.

6. Page 5 Line 22-23: 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: 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 in precipitation measurement by CSPGs, specifically in high mountain environments, therefore the above mentioned $P_w$, $P_e$ and $P_l$ values were assumed to be constant in the computation equations.

8. Page 6 Line 9: Authors' response: The catch ratio ($CR$) is defined in the end of the next paragraph, more suitable place.

Author's changes in manuscript: The catch ratio uses CSPGDFIR as the reference ($CR$ is a value between 0 and 1).
9. Page 6 Line 14-15:

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:

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 ($\alpha$) of the F-test is below 0.05, the fitted equation is significant. The lower the $\alpha$ value, the greater the significance.

11. Page 7 Line 2:

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:

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 CSPGPIT caught 4.7% and 3.4% more rainfall than the CSPGUN and the CSPGSA respectively ((CSPGPIT-CSPGUN)/CSPGUN*100; similarly hereinafter).
The CSPGSA caught 1.3% more rainfall than the CSPGUN (Table 3).

During the period from September 2012 to April 2015, the CSPGSA, CSPGPIT and CSPGDIFR caught 0.9%, 4.5% and 3.4% more rainfall, respectively, than the CSPGUN, and the CSPGPIT and CSPGDIFR caught 3.6% and 2.5% more rainfall, respectively, than the CSPGSA. However, the CSPGDIFR caught 1.0% less rainfall than the CSPGPIT (Table 3, Fig.2). These comparative results indicate that the CSPGPIT caught more rainfall and total precipitation compared to the CSPGDIFR 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 CSPGSA, CSPGPIT and CSPGDIFR caught 11.1%, 16.0% and 20.6% more snowfall, respectively, than the CSPGUN, and the CSPGPIT and CSPGDIFR caught 4.4% and 8.5% more snowfall, respectively, than the CSPGSA (Table 3).

Although the CSPGDIFR caught 3.9% more snowfall compared to the CSPGPIT (Table 3), the difference in total snowfall (43 events) between the CSPGDIFR and CSPGPIT was only about 3.4 mm (Table 3). Their linear correlation was highly significant with an R² 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 CSPGPIT 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: CSPGPIT > CSPGDIFR > CSPGSA > CSPGUN, while for snowfall their ranking was CSPGDIFR > CSPGPIT > CSPGSA > CSPGUN.

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**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.
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.

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 $\alpha=0.25$ (Table 4).

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 ($\alpha$) of the F-test is below 0.05, the fitted equation is significant. The lower the $\alpha$ 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 ($\alpha$) 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: 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: 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: 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 CSPGDFIR. From most to least rainfall and mixed precipitation measured, their ranking was CSPGPIT > CSPGDFIR > CSPGSA > CSPGUN, whereas in the snowy season, better wind shielding increased the snow catch, leading to CSPGDFIR > CSPGPIT > CSPGSA > CSPGUN.

20. Page 13 Line 21: 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 CSPGPIT could be used as a reference gauge because of its high catch ratio, simplicity and lower maintenance requirements.

Authors' response: Ok.

Author's changes in manuscript: ... the CSPGPIT 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

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: ...

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Abbreviation</th>
<th>Size ((\phi) denotes orifice diameter and (h) is observation height)</th>
<th>Start date</th>
<th>End date</th>
<th>Observation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unshielded China standard precipitation gauge (CMA, 2007a)</td>
<td>CSPGUN</td>
<td>(\phi=20\text{cm}, h=70\text{cm})</td>
<td>Jun 2009</td>
<td>Apr, 2015</td>
<td>20:00 and 08:00, Local time</td>
</tr>
<tr>
<td>Single Alter shield (Struizer, 1971) around a CSPG</td>
<td>CSPGSA</td>
<td>(\phi=20\text{cm}, h=70\text{cm})</td>
<td>Jun 2009</td>
<td>Apr, 2015</td>
<td>20:00 and 08:00, Local time</td>
</tr>
<tr>
<td>A CSPG in a Pit (Sevruk and Hamon, 1984)</td>
<td>CSPGPIT</td>
<td>(\phi=20\text{cm}, h=0\text{cm})</td>
<td>Sep 2010</td>
<td>Apr, 2015</td>
<td>20:00 and 08:00, Local time</td>
</tr>
<tr>
<td>DFIR shield (Goodison et al., 1998) around a CSPG</td>
<td>CSPGDFIR</td>
<td>(\phi=20\text{cm}, h=3.0\text{m})</td>
<td>Sep 2012</td>
<td>Apr, 2015</td>
<td>20:00 and 08:00, Local time</td>
</tr>
</tbody>
</table>

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: ...
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 ($\alpha$) of the F-test is below 0.05, the fitted equation is significant. The lower the $\alpha$ 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 ($\alpha$) 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 (CSPGUN; orifice diameter=20 cm, height=70 cm), (2) a single Alter shield around a CSPG (CSPGSA), (3) a CSPG in a pit (CSPGPI T) and (4) a Double-Fence International Reference (DFIR) shield with a Tretyakov-shielded CSPG (CSPGDFIR). The catch ratio (CR) used the CSPGDFIR as a reference (CR=CSPGX/CSPGDFIR, %; X denotes UN, SA or PIT). The results show that the CSPGSA, CSPGPI T and CSPGDFIR 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 CSPGUN from September 2012 to April 2015. The CSPGPI T and CSPGDFIR 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 CSPGSA. However, the CSPGDFIR caught 1.0% less rainfall, 1.2% less mixed precipitation, 3.9% more snowfall and 0.6% less total precipitation than the CSPGPI T. From most to least precipitation measured, the instruments ranked as follows: for rain and mixed precipitation, CSPGPI T > CSPGDFIR > CSPGSA > CSPGUN; for snowfall, CSPGDFIR > CSPGPI T > CSPGSA > CSPGUN. 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 CRUN/DFIR and CRSA/DFIR for rainfall decreased slightly. For mixed precipitation, the wind speed showed no significant effect on CRUN/DFIR and CRSA/DFIR below 3.5m/s. For snowfall, the CRUN/DFIR and CRSA/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 CSPGPI T 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 CRPI T/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 CRUN/DFIR and CRSA/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 in precipitation 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.
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 installations 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 Compare 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: 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

   
   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: This suggests that the CSPG \textsubscript{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 \textsubscript{PIT} and CSPG \textsubscript{DIFR}. Secondly, CSPG \textsubscript{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 \textsubscript{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\textsubscript{PIT} could be used as a reference gauge for snow precipitation events
at the experimental site.

6. Page 10 Line 5:  
   \underline{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:  
   \underline{Where CR_{CSPGUN,Rain} and CR_{CSPGSA,Rain} is the rainfall catch ratio (%) of the CSPG\textsubscript{UN} and the CSPG\textsubscript{SA}, respectively.}  

**Editor comments:** what time scale here???

**Authors' response:** Per observation.

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

8. Page 10 Line 23:  
   \underline{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:  
   \underline{1 when } $\alpha < 0.10$.  
   : 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:

**Editor comments:**

1) similar to equations below, you need to consider calm 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 $\alpha$ value. In this case, we used the SPSS outputs to calculate F-value, then use FDIST function in Microsoft Excel to calculate the $\alpha$ 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 ($\alpha$) of the F-test is below 0.05, the fitted equation is significant. The lower the $\alpha$ 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 ($\alpha$) 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):

$$CR_{S4/DFIR,Rain} = 0.188W_{s10}^3 - 0.719W_{s10}^2 + 0.551W_{s10} + 100 \quad 0<W_{s10}<7.4 \quad (10)$$

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

$$CR_{UN/DFIR,Mixed} = 100e^{-0.04W_{s10}} \quad 0<W_{s10}<5.9 \quad (11)$$

$$CR_{S4/DFIR,Mixed} = 100e^{-0.04W_{s10}}$$
Eq.(14) and Eq. (15) are revised as Eqs.(13) and (14):

\[ CR_{UN/DFIR,Mixed} = 100e^{-0.12W_{s,0.7}} \quad 0<W_{s,0.7}<2.9 \]  
\[ CR_{SA/DFIR,Mixed} = 100e^{-0.07W_{s,0.7}} \quad 0<W_{s,0.7}<2.9 \]  

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

\[ CR_{UN/DFIR,Snow} = 100e^{-0.08W_{s,10}} \quad 0<W_{s,10}<4.8 \]  
\[ CR_{SA/DFIR,Snow} = 100e^{-0.02W_{s,10}} \quad 0<W_{s,10}<4.8 \]  

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

\[ CR_{UN/DFIR,Snow} = 100e^{-0.11W_{s,0.7}} \quad 0<W_{s,0.7}<3.1 \]  
\[ CR_{SA/DFIR,Snow} = 100e^{-0.03W_{s,0.7}} \quad 0<W_{s,0.7}<3.1 \]  

b) Fig.5–Fig. 7 are redrawn:

c) Related tables and text is revised too.

![Figure 5](image)

**Figure 5.** Catch ratios (CRs) vs. wind speed for the rainfall event (a and b) and the daily rainfall (c and d) at gauge height. The solid line indicates the best fit to the data.
(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) greater than 1.0 mm.
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.

<table>
<thead>
<tr>
<th>Temporal scale</th>
<th>Phase</th>
<th>Gauges</th>
<th>Catch ratio (CR) vs. wind speed relationships</th>
<th>P (mm)</th>
<th>No. of events</th>
<th>F-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain</td>
<td>CSPG120</td>
<td>$CR_{\text{CSPG120}} = 0.188W^{0.256} - 0.795W^{10} + 100^{0.7}$</td>
<td>$R^2 = 0.97042$</td>
<td>$P &gt; 0.05$</td>
<td>103</td>
<td>α = 0.9623</td>
</tr>
<tr>
<td>Mixed</td>
<td>CSPG120</td>
<td>$CR_{\text{CSPG120}} = 0.188W^{0.256} - 0.795W^{10} + 0.55W^{10} + 100^{0.7}$</td>
<td>$R^2 = 0.99608$</td>
<td>$P &gt; 0.05$</td>
<td>24</td>
<td>α = 0.5683</td>
</tr>
<tr>
<td>Snow</td>
<td>CSPG120</td>
<td>$CR_{\text{CSPG120}} = 0.150W^{0.43} - 0.425W^{10} + 1.11W^{10} + 100^{0.7}$</td>
<td>$R^2 = 0.924008$</td>
<td>$P &gt; 0.05$</td>
<td>27</td>
<td>α = 0.47 no data</td>
</tr>
<tr>
<td>Mixed</td>
<td>CSPG120</td>
<td>$CR_{\text{CSPG120}} = 100e^{-0.048W^{10}}$</td>
<td>$R^2 = 0.49819$</td>
<td>$P &gt; 0.05$</td>
<td>90</td>
<td>α = 1.76 x 10^{-5}</td>
</tr>
<tr>
<td>Daily precipitation</td>
<td>CSPG120</td>
<td>$CR_{\text{CSPG120}} = 100e^{-0.048W^{10}}$</td>
<td>$R^2 = 0.49819$</td>
<td>$P &gt; 0.05$</td>
<td>21</td>
<td>α = 0.562</td>
</tr>
<tr>
<td>Mixed</td>
<td>CSPG120</td>
<td>$CR_{\text{CSPG120}} = 100e^{-0.048W^{10}}$</td>
<td>$R^2 = 0.49819$</td>
<td>$P &gt; 0.05$</td>
<td>6</td>
<td>α = 0.4073</td>
</tr>
<tr>
<td>Snow</td>
<td>CSPG120</td>
<td>$CR_{\text{CSPG120}} = 100e^{-0.048W^{10}}$</td>
<td>$R^2 = 0.49819$</td>
<td>$P &gt; 0.05$</td>
<td>6</td>
<td>α = 0.4073</td>
</tr>
</tbody>
</table>

* $W_{10}$: Wind speed during period of precipitation at 10 m height, $W_{0.7}$: Daily mean wind speed at gauge height (0.7 m for CSPG).
11. Page 12 Line 10-15:

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$^{-1}$. For the Hulu watershed site, daily mean wind speeds ($W_{m}$) 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

12. Page 12 Line 24:

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 $W_{s,10}$ 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 13 Line 17:

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:

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: 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: 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); Sep 16, 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 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).

17. Page 14 Line 12: 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_{PIT}. The with

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.
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

![Map of China with snowfall distribution](image)

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

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).

<table>
<thead>
<tr>
<th>Element</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Yearly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monthly precipitation (mm)</td>
<td>3.5</td>
<td>2.5</td>
<td>11.0</td>
<td>8.8</td>
<td>67.7</td>
<td>69.6</td>
<td>87.1</td>
<td>111.6</td>
<td>57.7</td>
<td>18.0</td>
<td>20.7</td>
<td>1.0</td>
<td>447.2</td>
</tr>
<tr>
<td>Monthly mean air temperature (°C)</td>
<td>-12.4</td>
<td>-7.7</td>
<td>-4.4</td>
<td>2.2</td>
<td>7.0</td>
<td>11.2</td>
<td>12.5</td>
<td>12.1</td>
<td>8.0</td>
<td>1.4</td>
<td>-5.6</td>
<td>-11.3</td>
<td>1.1</td>
</tr>
<tr>
<td>Monthly mean daily maximum air temperature (°C)</td>
<td>-4.0</td>
<td>0.7</td>
<td>3.5</td>
<td>10.3</td>
<td>14.3</td>
<td>18.2</td>
<td>19.5</td>
<td>19.7</td>
<td>15.4</td>
<td>10.2</td>
<td>3.6</td>
<td>--1.9</td>
<td>9.1</td>
</tr>
<tr>
<td>Monthly mean daily minimum air temperature (°C)</td>
<td>-19.0</td>
<td>-14.8</td>
<td>-11.6</td>
<td>-5.2</td>
<td>0.6</td>
<td>4.9</td>
<td>6.8</td>
<td>5.8</td>
<td>1.8</td>
<td>-5.5</td>
<td>-12.7</td>
<td>-18.2</td>
<td>-5.6</td>
</tr>
<tr>
<td>Monthly mean wind speed at the 1.5m height (m s⁻¹)</td>
<td>1.79</td>
<td>1.96</td>
<td>2.30</td>
<td>2.55</td>
<td>2.42</td>
<td>1.98</td>
<td>1.82</td>
<td>1.81</td>
<td>1.93</td>
<td>1.81</td>
<td>2.08</td>
<td>1.96</td>
<td>2.03</td>
</tr>
<tr>
<td>Monthly mean wind speed at the 2.5m height (m s⁻¹)</td>
<td>1.79</td>
<td>2.02</td>
<td>2.43</td>
<td>2.77</td>
<td>2.65</td>
<td>2.16</td>
<td>2.04</td>
<td>2.02</td>
<td>2.16</td>
<td>1.99</td>
<td>2.19</td>
<td>2.01</td>
<td>2.18</td>
</tr>
<tr>
<td>Monthly potential evaporation (mm)</td>
<td>31.6</td>
<td>47.0</td>
<td>79.4</td>
<td>124.4</td>
<td>140.9</td>
<td>155.0</td>
<td>141.7</td>
<td>127.0</td>
<td>101.6</td>
<td>75.2</td>
<td>47.3</td>
<td>31.0</td>
<td>1102.2</td>
</tr>
</tbody>
</table>

21. Page 26 Fig.5:

**Editor comments:** for a) and b), no data for winds 8-10 m/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 Tibetan Plateau. Precipitation gauges included (1) an unshielded Chinese standard precipitation gauge CSPG (CSPGUN; orifice diameter=20 cm, height=70 cm), (2) a single Alter shield around a CSPG (CSPGSA), (3) a CSPG in a pit (CSPGPIT) and (4) a Double-Fence International Reference (DFIR) shield with a Tretyakov-shielded CSPG (CSPGDFIR). The catch ratio (CR) uses CSPGDFIR as a reference (CR=CSPGX/CSPGDFIR, %; X denotes UN, SA or PIT). The intercomparison experiments show that the CSPGSA, CSPGPIT and CSPGDFIR 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 CSPGUN from September 2012 to April 2015, respectively. The CSPGPI and the CSPGDFIR 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 CSPGSA, respectively. Whereas, however, the CSPGDFIR caught 1.0% less rainfall, 1.2% less mixed precipitation, 3.9% more snowfall and 0.6% less total precipitation than the CSPGPIT, respectively. From most to least precipitation measured, the instruments ranked as follows: for rain and mixed precipitation, CSPGPIT >

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CSP\textsubscript{DFIR} > CSP\textsubscript{SA} > CSP\textsubscript{UN}; for snowfall, CSP\textsubscript{DFIR} > CSP\textsubscript{PIT} > CSP\textsubscript{SA} > CSP\textsubscript{UN}. From most to least rain and mixed precipitation, the measurements are ranked as follows: CSP\textsubscript{PIT} > CSP\textsubscript{DFIR} > CSP\textsubscript{SA} > CSP\textsubscript{UN}. For the snowfall, it follows as: CSP\textsubscript{DFIR} > CSP\textsubscript{PIT} > CSP\textsubscript{SA} > CSP\textsubscript{UN}. The CSP\textsubscript{DFIR} is used as reference to calculate the catch ratios (CRs) of the CSP\textsubscript{UN}, CSP\textsubscript{SA} and CSP\textsubscript{PIT}. The CR vs. 10m wind speed during the period of precipitation indicates that with increasing wind speed from 0 to 8.0m/s, the rainfall CR\textsubscript{UN/DFIR} or CR\textsubscript{SA/DFIR} for rainfall decreased slightly. For the mixed precipitation, wind speed showed no significant effect on CR\textsubscript{UN/DFIR} or CR\textsubscript{SA/DFIR} below 3.5m/s. For the snowfall, the CR\textsubscript{UN/DFIR} or CR\textsubscript{SA/DFIR} vs. wind speed shows that CR decreases 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 CSP\textsubscript{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\textsubscript{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\textsubscript{UN/DFIR} and CR\textsubscript{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 CSP\textsubscript{UN} and CSP\textsubscript{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 CSP\textsubscript{UN} and the CSP\textsubscript{SA} as reference gauges for snowfall and rainfall, respectively, could enhance precipitation observation precision. Applicable regions for the CSP\textsubscript{PIT} or the CSP\textsubscript{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

### 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 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). 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. But this reference which did not accurately show the correct amount 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. The gauge in the pit caught 6% more precipitation than the normally exposed gauge. In the second WMO precipitation measurement intercomparison (Rain, 1972–1976), the 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 gauges configuration (Goodison et al., 1998). In the fourth WMO precipitation measurement intercomparison (Rain Intensity, 2004–2008), different principles were tested to measure rainfall intensity and define a standardised adjustment procedure (Lanza et al., 2005). Because automation of precipitation measurements are widespread, the WMO Commission for Instruments and Methods of Observation (CIMO) organized the WMO Solid Precipitation Intercomparison Experiment (WMO-SPICE; Wolff et al., 2014) to define and validate automatic field instruments as references for gauge intercomparison, and to assess automatic systems and 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 WMO-SPICE project still selected the DFIR shield as 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 firstly compared by using the DFIR shield as a reference configuration in 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 losses, 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 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 varied from about 4.8 m to 3837 m) using the pit as a reference across over China, and a total of 29,000 precipitation events had been 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 20,000 precipitation events had been observed. However, the DFIR was not used as reference configurations, and there were only 3 stations located in the West Cold Regions of China (Chen et al., 2006) where the solid precipitation often occurred. Blowing snow and thick snow cover have traditionally limited the pit’s use as a reference shield for snowfall and mixed precipitation (snow with rain, rain with snow). Ye et al. (2004, 2007) developed a bias error adjusting method based on the observed data from 1987 to 1992 at the Tianshan valley site, and they found a new precipitation trend according to the adjusted
precipitation data over the past 50 years in China (Ding et al., 2007). The new adjusted precipitation would change the knowledge on water balance in many basins in China (Tian et al., 2007; Ye et al., 2012).

Although adjustment procedures and reference measurements were developed in several WMO international precipitation measurement intercomparisons (Goodison et al., 1998; Sevruk et al., 2009; Yang, 2014). 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 the experimental results from the eastern Tianshan China (Yang et al., 1991) to correct for the wind-induced errors on Tibetan Plateau. However, their precipitation gauges used for the neighbouring countries were the Tretyakov, MK2, Nepal and Indian standard and U.S. 8” in the neighbouring countries. As the third polar region in the world, the Tibetan Plateau and its surrounding mountain ranges are 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 CSPG is the standard manual precipitation gauge that has been used by the China Meteorological Administration (CMA) at 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 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 in precipitation 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 was selected as the reference for all precipitation types. The intercomparison experiments tested and assessed existing bias adjustment procedures for the CSPG and the SA shield around a CSPG (CSPG-SA).

2 Experiments and methods

2.1 Intercomparisons 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 established since in 2008 in the Hulu watershed. The annual mean precipitation is about 447.2 mm during 2010-2012 and concentrated during the warm season from May to September at this site. The annual mean temperature is approximately 0.41 °C, with a July mean (Tmean) of 4.12.5 °C and a January mean of -4.12.4°C over the years (Table 1). The annual potential evaporation ability (Eo) is about 1102 mm (Table 1).

The intercomparative experiments included (1) an unshielded CSPG (CSPGU; orifice diameter=20 cm, height=70 cm), (2) a Single Alter shield around a CSPG (CSPGSA), (3) a CSPG in a pit
(CSPG\textsubscript{PIT}), and (4) a DFIR shield with a Tretyakov-shielded CSPG (CSPG\textsubscript{DFIR}) (Fig.1, Table 2). The CSPG\textsubscript{UN}, CSPG\textsubscript{SA} and CSPG\textsubscript{PIT} were installed before September 2010, whereas the CSPG\textsubscript{DFIR} was installed in September 2012 (Table 2). In the cold season (October to April), snowfalls dominated the precipitation events, and in the warm season (May to September), rainfall was dominated. The precipitation amount ($P$) was measured manually twice a day at 08:00 and 20:00 LT (local time) (Beijing time) according to the CMA's criterion (CMA, 2007a). In the warm season, $P$-precipitation was measured by volume. Whereas in the cold season, the funnel and glass bottle were removed from the CSPG and precipitation was weighed under a windproof box to avoid wind effects. If there is any frost on the outside surface of the collector, it will be wiped up by offusing 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) were distinguished by observer according to the CMA’s criterion (CMA, 2007b). This method has been used since the 1950s at 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 $T_{\text{max}}$ and minimum $T_{\text{min}}$, have been measured conforming to the meteorological observation manual Relevant variables such as air temperature (maximum and minimum; $T_{\text{max}}$ and $T_{\text{min}}$) have been observed manually at the site since June, 2009. A meteorological tower 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 observed every 30 seconds and were saved as half-hourly values (sum or mean) obtained. The specific meteorological conditions at the site are summarized in Table 1.

![Fig.1 about here](image1)

Table 1 and Table 2 about here

### 2.2 Adjustment methods

This field experiment focuses on two key aspects. One is a comparison among of the CSPG\textsubscript{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 the general formula as:

\[ P_c = K P_g + \Delta P_e + \Delta P_r + \Delta P_t = P_{DFIR} + \Delta P_w + \Delta P_e + \Delta P_t \]  \hspace{1cm} (1)

Where \( P_c \) is the adjusted precipitation, \( K \) is the wind-induced coefficient and \( P_g \) is the gauge-measured precipitation. \( P_w \) is the wetting loss, \( P_e \) is the evaporation loss, \( P_t \) is trace precipitation and \( PDFIR \) is the DFIR-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 the measurements at the Tianshan valley site (Yang, 1988; Yang et al., 1991). Ren and Li (2007) reported the 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 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 in precipitation 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 (\( W_{gs} \text{ m s}^{-1} \)) at the gauge height and the daily maximum and minimum temperatures (\( T_{max}, T_{min} \text{ °C} \)). The WMO has given Eqs.(2)-(4) for the shielded Tretyakov gauge catch ratio versus daily wind speed (\( W_{gs} \text{ m s}^{-1} \)) at gauge height, and daily maximum and minimum temperatures (\( T_{max}, T_{min} \text{ °C} \)) on a daily time step for various precipitation types (Yang et al., 1995; Goodison et al., 1998). These equations can be used over a great range of environmental conditions (Goodison et al., 1998). Therefore, in this paper, the catch ratio (CR, %) follows their definition by using CSPG_{DFIR} as
\[ CR_{\text{snow}} = 103.1 - 8.67W_s + 0.3T_{\text{max}} \]  
\[ CR_{\text{mix}} = 96.99 - 4.46W_s + 0.88T_{\text{max}} + 0.22T_{\text{min}} \]  
\[ CR_{\text{rain}} = 100.0 - 4.77W_s^{0.56} \]

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

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

\[ CR_{\text{snow}} = 100 \exp(-0.056W_s^1) \quad (0 < W_s < 6.2) \]  
\[ CR_{\text{rain}} = 100 \exp(-0.04W_s^1) \quad (0 < W_s < 7.3) \]  
\[ CR_{\text{mix}} = CR_{\text{snow}} - (CR_{\text{snow}} - CR_{\text{rain}})(T_{\text{mean}} + 2) / 4 \]

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

Referring to Eqs.(2)-(7), in this paper, two types of equations were used. 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 revised version of the Eqs.(5)-(7). Another type is similar to Eqs.(2)-(4), which use the daily mean wind speed at gauge height. For the CSPGs, the gauge height was 70 cm (Table 2). The catch ratio uses CSPG_{DFIR} as the reference \((CR=CSPG_{X}/CSPG_{DFIR} \%, X \text{ denotes UN, SA or PIT})\). 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 \((\alpha)\) of the F-test is below 0.05, the fitted equation is significant. The lower the \(\alpha\) 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 \((W_{s2.5})\), according to the Monin-Obukhov theory and the gradient method (Bagnold, 1941; Dyer and Bradley, 1982):

\[ W_{sZ} = \frac{\ln Z - \ln Z_0}{\ln 1.5 - \ln Z_0} W_{s1.5} \]  
\[ \ln Z_0 = \frac{W_{s2.5} \ln 1.5 - W_{s1.5} \ln 2.5}{W_{s2.5} - W_{s1.5}} \]  

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 CSPGU, CSPGSA, and CSPGPIT, respectively (Table 3). Snow occurred 84 times, mixed precipitation occurred 44 times, and rain occurred 480 times during this period. From September 2012 to April 2015, a subset of 283 precipitation events were recorded for the CSPGU, CSPGSA, CSPGPIT, and CSPGDFIR gauges, respectively (Table 3). During this period, snow occurred 43 times, mixed precipitation occurred 29 times, and rainfall occurred 211 times.

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 installations 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

3.2.1 Precipitation gauge intercomparison for rainfall Rainfall

Good linear correlations are found among the four CSPG installations (Fig.2). From September 2010 to April
2015, the CSPGPIT caught 4.7% and 3.4% more rainfall than the CSPGUN and the CSPGSA respectively ((CSPGPIT-CSPGUN)/CSPGUN*100; similarly hereinafter). The CSPGSA caught 1.3% more rainfall than the CSPGUN (Table 3).

During the period from September 2012 to April 2015, the CSPGSA, CSPGPIT and CSPGDIFR caught 0.9%, 4.5% and 3.4% more rainfall, respectively, than the CSPGUN, and the CSPGPIT and CSPGDIFR caught more 3.6% and 2.5% rainfall, respectively, than the CSPGSA (Fig.2). These comparative studies results indicate that CSPGPIT catches more rainfall and total precipitation compared to the CSPGDIFR and other gauges at the experimental site (Table 3, Fig.2).

3.2.2 Precipitation gauge intercomparison for mixed precipitation

From September 2012 to April 2015, a total of 29 mixed precipitation events were observed. As shown in Table 3, the CSPGPIT 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 CSPGDIFR. The linear relationship between the CSPGPIT and CSPGDIFR is statistically significant with an $R^2$ value of about 0.98 (Fig.3f). Thus for mixed precipitation, in addition to the CSPGDIFR, the CSPGPIT could also be selected as a reference gauge for the CSPGUN and CSPGSA at the experimental site.

From September 2010 to April 2015, a total of 44 mixed precipitation events were observed. The CSPGPIT caught 12.1% and 5.6% more mixed $P$ than the CSPGUN and the CSPGSA, respectively. The CSPGSA caught 6.1% more mixed $P$ than the CSPGUN (Table 3). From September 2012 to April 2015, the CSPGSA–CSPGPIT and CSPGSA–CSPGDIFR caught 7.7%, 15.6% and 14.2% more mixed $P$ than the CSPGUN, respectively. The CSPGPIT and the CSPGDIFR caught more 7.3% and 6.0% mixed $P$ than the CSPGSA, respectively. Whereas the CSPGDIFR caught 1.2% less mixed $P$ than the CSPGPIT (Table 3).

Good linear correlations are observed among the gauges (Fig.3). The CSPGPIT caught 1.1 mm more mixed precipitation than the CSPGDIFR 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 CSPGPIT instead of the CSPGDIFR could be selected as the reference gauge for the CSPGUN and the CSPGSA at the experimental site.

Fig.3 about here

3.2.3 Precipitation gauge intercomparison for snowfall
From September 2010 to April 2015, a total of 84 snowfall events are observed. The CSPG_PIT caught 21.0% and 6.4% more snowfall than the CSPG_UN and the CSPG_SA respectively. The CSPG_SA caught 13.7% more snowfall than the CSPG_UN (Table 3). During the period 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, respectively. The CSPG_PIT and the CSPG_DIFR 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_DIFR 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_DIFR (CSPG_DIFR=1.029CSPG_PIT, R²=0.994). Although the CSPG_DIFR caught 3.9% more snowfall than compared to the CSPG_PIT (Table 3), the difference of total snowfall (43 events) between the CSPG_DIFR and the CSPG_PIT was only about 3.4 mm (Table 3). Their linear correlation was very significant with a R² 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.

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_DIFR> CSPG_SA> CSPG_UN, while for snowfall their ranking was CSPG_DIFR> CSPG_PIT> CSPG_SA> CSPG_UN.

### 3.3-3.4 Catch ratio vs. wind speed

Previous studies showed that wind speed during the precipitation period is the most significant variable affecting gauge catch efficiency (Metcalfe and Goodison, 1993; Yang et al., 1995; Goodison et al., 1998). As described above, the wind-induced error of CSPG measurement has not been well tested. Because the CMA stations observe wind speeds at the 10 m height, so the CSPG_UN and the CSPG_SA adjustment equations for a single precipitation event are 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 also established, based on the daily mean wind speed converted to the data at gauge height (0.7 m for the CSPG, it is 0.7 m) and air temperature data.
To minimize ratio scatter 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, in the Hulu watershed, most snowfall and mixed precipitation events were less than 3.0 mm. For this reason, the limit was reduced and, single or daily snowfall and mixed precipitation greater than 1.0 mm were chosen to use in this chapter selected. Whereas, for the rainfall, precipitation events greater than 3.0 mm were selected.

The numbers of the chosen 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 summarized in Table 4 too. The CR\textsubscript{UN/DFIR} and CR\textsubscript{SA/DFIR} vs. wind speed are statistically significant, but the As shown in Table 4, all the CR\textsubscript{PIT/DFIR} vs. \(W_{0.7}\) or \(W_{10}\) relationships do not pass the F-test when \(\alpha=0.10\). This phenomenon indicates that both PIT and DFIR are effective in preventing wind from influencing the gauge catch of precipitation, therefore the CR\textsubscript{PIT/DFIR} is not related to wind speed. Therefore, only CR\textsubscript{UN/DFIR} and CR\textsubscript{SA/DFIR} vs. wind speed relations are discussed in the following text.

The catch ratio vs. wind speed for rainfall vary from 80% to 110%. With increasing wind speed, the CRs decreased 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\textsubscript{UN} and CSPG\textsubscript{SA}, respectively. They both pass the F-test when \(\alpha<0.1\) (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 (\(\alpha\)) was obtained by using the FDIST function in Microsoft Excel. Other forms such as the exponential expression were treated in a similar way.

\[
\text{CR}_{\text{UN/DFIR,Rain}} = 0.188W_{10}^3 - 0.719W_{10}^2 + 0.551W_{10} + 100 \quad 0<W_{10}<7.4 \\
\text{CR}_{\text{SA/DFIR,Rain}} = 0.188W_{10}^3 - 2.027W_{10}^2 + 5.554W_{10} + 94.27 \quad 0<W_{10}<7.4
\]

Where \(\text{CR}_{\text{UN/DFIR,Rain}}\) and \(\text{CR}_{\text{SA/DFIR,Rain}}\) is the rainfall catch ratio (%) per observation of the CSPG\textsubscript{UN} and the
CSPGSA, 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 do not pass the F-test even with \( \alpha=0.25 \) (Table 4).

3.4.2 Mixed precipitation catch ratio vs. wind speed

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

Fig.6 about here

$$\begin{align*}
CR_{UN/DFIR,Mixed} &= 100e^{-0.06W_{s10}} & 0<W_{s10}<5.9 \\
CR_{SA/DFIR,Mixed} &= 100e^{-0.04W_{s10}} & 0<W_{s10}<5.9
\end{align*}$$

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 CSPGUN, Eq. (14) passes the F-test when with \( \alpha<0.10 \), whereas the Eq.(15) with an \( \alpha \) value of about 0.12 doesn't (Table 4).

$$\begin{align*}
CR_{UN/DFIR,Mixed} &= 100e^{-0.12W_{s0.7}} & 0<W_{s0.7}<2.9 \\
CR_{SA/DFIR,Mixed} &= 100e^{-0.07W_{s0.7}} & 0<W_{s0.7}<2.9
\end{align*}$$

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

$$\begin{align*}
CR_{UN/DFIR,Mixed} &= 13.83W_{s0.7}^{-4.91} + 1.25T_{max} - 0.88T_{min} + 62.21 & \alpha=0.20 \\
CR_{SA/DFIR,Mixed} &= 10.74W_{s0.7}^{-4.74} + 0.85T_{max} - 0.18T_{min} + 76.20 & \alpha=0.29
\end{align*}$$

Where \( T_{max} \) and \( T_{min} \) are the daily maximum and minimum air temperature (\(^\circ\)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 CSPGUN, the exponential relationship Eq.(18) passes the F-test when with \( \alpha<0.001 \).
The Eq. (18) is similar to Eq. (5) suggested by Yang et al. (1991). For the CSPGSA, its exponential expression in Eq. (18) resembles the power law expression Eq. (19) passes the F-test when \( \alpha < 0.05 = 0.07 \) (Table 4).

\[
CR_{UN/DFIR, Snow} = 100e^{-0.08W_{s0.7}} \quad 0 < W_{s0.7} < 4.8 \quad (18)
\]

\[
CR_{SA/DFIR, Snow} = 100e^{-0.02W_{s0.7}} \quad 0 < W_{s0.7} < 4.8 \quad (19)
\]

On daily scale, the relationships between snowfall CRs and wind speed at gauge height \( W_s \) are also exponential expressions (Table 4, Fig. 7). For the CSPGUN and the CSPGSA, the Eqs. (19) and Eq. (20) pass the F-test when \( \alpha < 0.001 \) and \( \alpha < 0.10 = 0.14 \), respectively (Table 4). Eqs. (18) - (21) could therefore be directly used to calibrate the wind-induced snowfall measurement errors for CSPGUN and the CSPGSA.

\[
CR_{UN/DFIR, Snow} = 100e^{-0.11W_{s0.7}} \quad 0 < W_{s0.7} < 3.1 \quad (20)
\]

\[
CR_{SA/DFIR, Snow} = 100e^{-0.03W_{s0.7}} \quad 0 < W_{s0.7} < 3.1 \quad (21)
\]

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

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

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

From the above mentioned relationships of \( CR_{UN/DFIR, Snow} \) and \( CR_{SA/DFIR, Snow} \) 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 the valley Tianshan site of Tianshan. Their results indicated that the ratios of CSPGDFIR/CSPGUN ratios for snowfall and mixed precipitation were 1.222 and 1.160, respectively. In the Hulu watershed, these ratios of CSPGDFIR/CSPGUN for snowfall and mixed precipitation were 1.165 (Fig. 4c) and 1.072 (Fig. 3c), and the while those ratios of for
CSPGPIT/CSPGUN for 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 ($W_{10}$) 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 the Hulu watershed site, daily mean wind speeds ($W_{10}$) on precipitation days never exceeded 3.56 m s$^{-1}$, and over 98.955.2% of the precipitation events occurred when daily mean wind speeds were below 3 m s$^{-1}$. During the period of precipitation, the largest wind speed at 10 m height is about 8.8 m s$^{-1}$, and over 54.2% of the precipitation events occurred when wind speeds were below 3 m s$^{-1}$.

As Ren et al. (2003) reported, across 30 comparison stations in China, the CSPGPIT caught 3.2% (1.1~7.9%) more rainfall and 11.0% (2.2~24.8%) more snowfall compared to the CSPGUN. 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 CSPGPIT caught 7.9% more rainfall and 16.8% more snowfall than the CSPGUN from 1992 to 1998. In our study, the CSPGPIT captured 4.7% more rainfall, 21.0% more snowfall and 12.1% more mixed precipitation than the CSPGUN 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 ($W_{10}$) 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 $W_{10}$ 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 30 comparison stations in China, the CSPGPIT caught 3.2% (1.1~7.9%) more rainfall and 11.0% (2.2~24.8%) more snowfall than the CSPGUN. 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 CSPGPIT captured 4.7% more rainfall, 21.0% more snowfall, and 12.1% more mixed precipitation than the CSPGUN from 1992 to 1998. In our study, the CSPGPIT captured 4.7% more rainfall, 21.0% more snowfall, and 12.1% more mixed precipitation than the CSPGUN 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) due to differences in the wind regime.
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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 more rainfall and mixed precipitation than the CSPG DFIR. For the snowfall, the catch ratio for the CSPG Pit was 0.96, close to that of the CSPG DFIR catch ratio measurement. The difference of total snowfall (43 events) between the CSPG Pit and the CSPG DFIR 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 indicated, however, that for most of China the maximum snow depths in the past 30 years have been less than 20 cm (Li, 1999), and with average snow depths were less than 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 less than 15% of the annual precipitation amount. Ren and Liet al. (2002-2003) has reported, that among the 29276-2286 precipitation snowfall events, there are only 784-54 were blowing or drifting snow events accounting for about 2.7-2.4% at the 30-26 stations across China. Based on the regionalization of snow drift in China, these blowing or drifting snow events occur mostly in the central and south-western, south-eastern Tibetan Plateau, in the northern Xinjiang province and in north-eastern China.
In these regions, the CSPG\textsubscript{DFIR} should be used as a reference gauge. In other regions, the CSPG\textsubscript{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\textsubscript{PIT} and CSPG\textsubscript{DFIR} as reference gauges are shown in Fig. 10. The applicable regions for the CSPG\textsubscript{PIT} and the CSPG\textsubscript{DFIR} as reference gauges are shown in Fig. 9 based on CMA snowfall and snow depth data.

4.3 Uncertainties Limitations of the this experiment

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

The wind speeds at gauge height and at the 10 m height were not observed directly, but they are calculated from the observed data at 1.5 m and 2.5 m heights according to the Monin-Obukhov theory and the gradient method (Eqs. (9)). Although this method is widely used, it is effective only under neutral atmospheric conditions. During the precipitation period from September 2012 to April 2015, the $Z_0$ was calculated using Eq. (9). The results showed the $Z_0$ to be about 0.06 m of the average but it varied from near zero to 0.67 m. As shown in Fig. 10, 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 $Z_0=0.5h$ 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).
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 intercomparison experiment in the Hulu watershed of the Qilian Mountains indicated that the CSPGPIT catches more rainfall, mixed precipitation and total precipitation but less snowfall than the CSPGDFIR. From most to the least rainfall and mixed precipitation measured, it can be ordered as CSPGPIT > CSPGDFIR > CSPGSA > CSPGUN. While in the snowy season, it follows the rule that better wind-shielding increased catch with more snow catch and they can be ordered: CSPGDFIR > CSPGPIT > CSPGSA > CSPGUN. The wind-induced bias of CSPGSA and the CSPGUN are well tested, and the most adjustment equations could be used. They would help to improve the precipitation accuracy in China.

In the regions with little snowfall, such as the south and central part of China (Zhang and Zhong, 2014), and the regions with a similar climate and environment to that of the Hulu watershed site, the CSPGPIT could be used as 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 south-eastern–central and south-western Tibetan Plateau where snowfall often occurs, the best choice for reference gauge would be the CSPGPIT for rainfall and CSPGDFIR 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 CRPIT/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.
Acknowledgments

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References


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


Yang, D., Shi, Y., Kang, E., Zhang, Y., and Yang, X.: Results of solid precipitation measurement intercomparison


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

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

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

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Abbreviation</th>
<th>Size (φ stand denotes orifice diameter and h signifies observation height)</th>
<th>Start date</th>
<th>End date</th>
<th>Measure Observation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unshielded China standard precipitation gauge (CMA, 2007a)</td>
<td>CSPGUN</td>
<td>φ=20cm, h=70cm</td>
<td>Jun 2009</td>
<td>Apr, 2015</td>
<td>20:00 and 08:00, LT</td>
</tr>
<tr>
<td>Single Alter shield (Struzer, 1971) around a CSPG</td>
<td>CSPGSA</td>
<td>φ=20cm, h=70cm</td>
<td>Jun 2009</td>
<td>Apr, 2015</td>
<td>20:00 and 08:00, LT</td>
</tr>
<tr>
<td>A CSPG in a Pit (Sevruk and Hamon, 1984)</td>
<td>CSPGPIT</td>
<td>φ=20cm, h=0cm</td>
<td>Sep 2010</td>
<td>Apr, 2015</td>
<td>20:00 and 08:00, LT</td>
</tr>
<tr>
<td></td>
<td>CSPG&lt;sub&gt;DFIR&lt;/sub&gt;</td>
<td>( \varphi = 20\text{cm}, h = 3.0\text{m} )</td>
<td>Sep 2012</td>
<td>Apr, 2015</td>
<td>time</td>
</tr>
<tr>
<td>-------------------------</td>
<td>----------------------</td>
<td>-----------------------------------------------</td>
<td>----------</td>
<td>-----------</td>
<td>---------------</td>
</tr>
<tr>
<td>DFIR shield (Goodison et al., 1998) around a CSPG</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20:00 and 08:00, Local time</td>
</tr>
</tbody>
</table>
Table 3. Summary of precipitation observations at the Hulu watershed intercomparison site, 2010-2015.

<table>
<thead>
<tr>
<th>Date/Phase</th>
<th>No. of Events</th>
<th>CSPG$_{UN}$ (mm)</th>
<th>CSPG$_{SA}$ (mm)</th>
<th>CSPG$_{PIT}$ (mm)</th>
<th>CSPG$_{DFIR}$ (mm)</th>
<th>CSPG$_{CR}$ (CR, %)</th>
<th>CSPG$_{DFIR}$ (CR, %)</th>
<th>CSPG$_{PIT}$ (CR, %)</th>
<th>CSPG$_{SA}$ (CR, %)</th>
<th>CR</th>
<th>CR</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep 2010 Ap 4</td>
<td>608</td>
<td>1986.8</td>
<td>26</td>
<td>6.5</td>
<td>2038.1</td>
<td>96.4</td>
<td>3.8</td>
<td>2115.1</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rain</td>
<td>480</td>
<td>1700.7</td>
<td>95.5</td>
<td>1.3</td>
<td>1723.4</td>
<td>96.7</td>
<td>3.4</td>
<td>1781.4</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mixed</td>
<td>44</td>
<td>139.9</td>
<td>89.2</td>
<td>6.1</td>
<td>148.5</td>
<td>94.7</td>
<td>5.6</td>
<td>156.8</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>snow</td>
<td>84</td>
<td>146.2</td>
<td>82.6</td>
<td>13.7</td>
<td>166.2</td>
<td>94.0</td>
<td>6.4</td>
<td>176.9</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sep 2012 Ap 5</td>
<td>283</td>
<td>1066.7</td>
<td>94.9</td>
<td>2.0</td>
<td>1088.4</td>
<td>96.9</td>
<td>3.9</td>
<td>1130.9</td>
<td>100.6</td>
<td>-0.6</td>
<td>1123.7</td>
<td>100</td>
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<tr>
<td>rain</td>
<td>211</td>
<td>920.7</td>
<td>96.7</td>
<td>0.9</td>
<td>928.6</td>
<td>97.5</td>
<td>3.6</td>
<td>961.8</td>
<td>101.0</td>
<td>-1.0</td>
<td>952.2</td>
<td>100</td>
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<tr>
<td>mixed</td>
<td>29</td>
<td>71.1</td>
<td>87.6</td>
<td>7.7</td>
<td>76.6</td>
<td>94.3</td>
<td>7.3</td>
<td>82.2</td>
<td>101.2</td>
<td>-1.2</td>
<td>81.2</td>
<td>100</td>
</tr>
<tr>
<td>snow</td>
<td>43</td>
<td>74.9</td>
<td>82.9</td>
<td>11.1</td>
<td>83.2</td>
<td>92.1</td>
<td>4.4</td>
<td>86.9</td>
<td>96.2</td>
<td>3.9</td>
<td>90.3</td>
<td>100</td>
</tr>
</tbody>
</table>
**Table 4.** Catch ratio (CR) vs. wind speed relationships at the Hulu watershed intercomparison site, 2012-2015.

<table>
<thead>
<tr>
<th>Temporal scale</th>
<th>Phase</th>
<th>Gauges</th>
<th>Catch ratio (CR) vs. wind speed relationships* ( P ) (mm)</th>
<th>No. of events</th>
<th>F-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain</td>
<td>Precipitation event</td>
<td>CSPGUN</td>
<td>( CR_{UN/DFIR,Rain} = 0.181 W_{10}^{0.3} - 0.256 W_{10}^{2} - 0.795 W_{10} + 100 ) ( R^2=0.020903 )</td>
<td>( P&gt;3.0 )</td>
<td>103</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSPGSA</td>
<td>( CR_{SA/DFIR,Rain} = 0.188 W_{10}^{0.3} - 0.719 W_{10}^{2} + 0.551 W_{10} + 100 ) ( R^2=0.099983 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSPGPIT</td>
<td>( CR_{PIT/DFIR,Rain} = 0.150 W_{10}^{0.3} - 0.425 W_{10}^{2} + 1.119 W_{10} + 100 ) ( R^2=0.023008 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed</td>
<td></td>
<td>CSPGUN</td>
<td>( CR_{UN/DFIR,Mixed} = 100 e^{-0.068 W_{10}} ) ( R^2=0.198194 )</td>
<td>( P&gt;1.0 )</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSPGSA</td>
<td>( CR_{SA/DFIR,Mixed} = 100 e^{-0.041 W_{10}} ) ( R^2=0.102100 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSPGPIT</td>
<td>( CR_{PIT/DFIR,Mixed} = 100 e^{-7.2 W_{10}} ) ( R^2=0.024000 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snow</td>
<td></td>
<td>CSPGUN</td>
<td>( CR_{UN/DFIR,Snow} = 100 W_{10}^{0.2} ) ( R^2=0.422090 )</td>
<td>( P&gt;1.0 )</td>
<td>2234</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSPGSA</td>
<td>( CR_{SA/DFIR,Snow} = 100 W_{10}^{0.2} ) ( R^2=0.422090 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSPGPIT</td>
<td>( CR_{PIT/DFIR,Snow} = 100 e^{-0.041 W_{10}} ) ( R^2=0.140024 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily precipitation</td>
<td>Rain</td>
<td>CSPGUN</td>
<td>( CR_{UN/DFIR,Rain} = -1.400 W_{10}^{0.3} + 2.987 W_{10}^{2} - 6.116 W_{10} + 100 ) ( R^2=0.045032 )</td>
<td>( P&gt;3.0 )</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSPGSA</td>
<td>( CR_{SA/DFIR,Rain} = -0.924 W_{10}^{0.3} + 1.158 W_{10}^{2} - 3.338 W_{10} + 100 ) ( R^2=0.022014 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSPGPIT</td>
<td>( CR_{PIT/DFIR,Rain} = -0.952 W_{10}^{0.3} + 1.503 W_{10}^{2} + 2.237 W_{10} + 100 ) ( R^2=0.012-0.00 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed</td>
<td></td>
<td>CSPGUN</td>
<td>( CR_{UN/DFIR,Mixed} = 100 e^{-0.12 W_{10}} ) ( R^2=0.469144 )</td>
<td>( P&gt;1.0 )</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSPGSA</td>
<td>( CR_{SA/DFIR,Mixed} = 100 e^{-0.07 W_{10}} ) ( R^2=0.422094 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSPGPIT</td>
<td>( CR_{PIT/DFIR,Mixed} = 100 e^{-0.001 W_{10}} ) ( R^2=0.042003 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snow</td>
<td></td>
<td>CSPGUN</td>
<td>( CR_{UN/DFIR,Snow} = 100 e^{-0.11 W_{10}} ) ( R^2=0.527477 )</td>
<td>( P&gt;1.0 )</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSPGSA</td>
<td>( CR_{SA/DFIR,Snow} = 100 e^{-0.03 W_{10}} ) ( R^2=0.444087 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CSPGPIT</td>
<td>( CR_{PIT/DFIR,Snow} = 100 e^{-0.01 W_{10}} ) ( R^2=0.022000 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*: \( W_{10} \)-Wind speed during period of precipitation at 10 m height; \( W_{0.7} \)-Daily mean wind speed at gauge height (0.7 m for CSPG).
Figure 1. Precipitation gauge intercomparison experiment in the Qilian Mountains, Tibetan Plateau.
Figure 2. Intercomparison plots among CSPG\textsubscript{UN}, CSPG\textsubscript{SA}, CSPG\textsubscript{PIT} and CSPG\textsubscript{DFIR} for the rainfall events from September 2010 (a, b and d) or September 2012 (c, e and f) to April 2015.
Figure 3. Intercomparison plots among CSPG\textsubscript{UN}, CSPG\textsubscript{SA}, CSPG\textsubscript{PIT} and CSPG\textsubscript{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\textsubscript{UN}, CSPG\textsubscript{SA}, CSPG\textsubscript{PIT} and CSPG\textsubscript{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 8. (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\textsubscript{PIT} and CSPG\textsubscript{DFIR} as reference gauges in China.
Figure 10. Surface roughness during the precipitation period from September 2012 to April 2015.