ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 24, NO. 3, 2007, 449–458

Errors and Correction of Precipitation Measurements in China

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(Received 3 April 2006; revised 16 September 2006)

ABSTRACT

In order to discover the range of various errors in Chinese precipitation measurements and seek a correction method, 30 precipitation evaluation stations were set up countrywide before 1993. All the stations are reference stations in China. To seek a correction method for wind-induced error, a precipitation correction instrument called the "horizontal precipitation gauge" was devised beforehand. Field intercomparison observations regarding 29,000 precipitation events have been conducted using one pit gauge, two elevated operational gauges and one horizontal gauge at the above 30 stations. The range of precipitation measurement errors in China is obtained by analysis of intercomparison measurement results. The distribution of random errors and systematic errors in precipitation measurements are studied in this paper.

A correction method, especially for wind-induced errors, is developed. The results prove that a correlation of power function exists between the precipitation amount caught by the horizontal gauge and the absolute difference of observations implemented by the operational gauge and pit gauge. The correlation coefficient is 0.99. For operational observations, precipitation correction can be carried out only by parallel observation with a horizontal precipitation gauge. The precipitation accuracy after correction approaches that of the pit gauge. The correction method developed is simple and feasible.

Key words: precipitation evaluation stations, intercomparison measurements, precipitation measurement errors, correction method

DOI: 10.1007/s00376-007-0449-3

1. Introduction

Precipitation data observed by rain gauges is a basis for the study of climate change (Wang et al., 2004), model and runoff simulation (Xiong et al., 2003; Liu et al., 2003), regional precipitation estimation (Li and Fu, 2005), and so on. The accuracy of precipitation observations is vital to such studies. However, there are various measurement errors in operational precipitation observations that affect their accuracy. In order to clearly establish precipitation measurement errors numerous national and regional studies have been conducted to assess measurement errors in solid, mixed and liquid precipitation (Allerup et al., 1980; Chvíla et al., 2002, 2005; Duchon and Essenberg, 2001; Molini et al., 2001; Nešpor and Sevruk, 1999; Sevruk, 1985; Sevruk and Klemm, 1989; Sevruk and Nevenic, 1998; Sevruk and Chvíla, 2005; Sevruk et al., 1994; Yang et al., 1995; Goodison et al., 1998). In 1971, an intercomparison study dealing with errors of liquid precipitation was initiated by the World Meteorological Organization (WMO), and the analyses resulted in construction of a statistical correction model generally applicable for correction of liquid precipitation (WMO, 1982). A similar WMO intercomparison study was initiated in 1986 leading to various suggestions for statistical correction models generally applicable for correction of solid and mixed precipitation (WMO, 1996; Goodison et al., 1998). Within the framework of the abovementioned WMO studies, statistical models for correction of liquid as well as solid and mixed precipitation were developed (Allerup et al., 1980, 1997, 2000; Michelson, 2004; Bogdanova et al., 2002; Molini et al., 2005).

Point measurements of precipitation serve as the primary source of data for aerial analysis. Therefore, accuracy is particularly vital in these measurements of precipitation. However, precipitation measurements are particularly sensitive to the size, shape and exposure of the rain gauge, as well as wind and topography, and so there are random observational and systematic

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errors in precipitation amounts. In terms of systematic errors, those due to systematic wind-field deformation above the gauge orifice are typically 2%–10% for rain and 10%–50% for snow, and the average error due to wetting loss on the internal walls of the collector and in the container when it is emptied can be up to 0.2 mm per observation (WMO, 1996). Wind-induced errors and wetting loss errors are the main types of systematic error in precipitation measurement. Besides these, however, there are other types of systematic error, such as evaporation from the container, blowing and drifting of snow, splashing in and splashing out of water, as well as some instrument errors (WMO, 1996).

Of all the above errors, wind-induced errors are the most difficult to correct. These occur because of wind-field deformation above the gauge orifice, which is above the ground, and are particularly sensitive to the size, orifice shape, and height of the gauge, as well as wind speed. Various sizes and shapes of orifice and various gauge heights are used in different countries, and thus measurements are not strictly comparable. A manual operational precipitation gauge is used in the Chinese conventional precipitation network, which has an open receptacle with vertical sides, in the form of a right cylinder, with a container and a removable funnel to measure the rain (the funnel is taken away to increase the collector depth for measuring snow). Its orifice area is always 314 cm^2, but installation heights above ground have varied. The installation height was 30 cm before 1951, 70 cm from 1951–1953 and after 1960, and 200 cm from 1954–1960. In addition, the gauges in China were equipped with wind shields from 1954–1960.

To establish a correction method for wind-induced errors, a precipitation correction instrument called the “horizontal precipitation gauge” was devised beforehand. If a circular plate is placed at a certain height over the operational gauge orifice, then the horizontal gauge is constructed as shown in Fig. 1a. Water particles can enter the operational gauge only from all sides under the circular plate. The water in the circular plate drains away through a thin pipe between the plate center and the gauge body, as shown in Fig. 1b, where R is the radius of the operational gauge orifice, r is the radius of the plate, K_1 is the coefficient size of the plate, h is the installation height from the plate to the operational gauge orifice, and K_2 is the installation height coefficient of the plate. Position A is the waterspout. As is commonly known, the stronger the wind speed, the bigger the falling angle; consequently, the greater the wind-induced error of a precipitation event measured by an elevated operational gauge. The precipitation amount from an elevated horizontal gauge is also related to precipitation angle, and consequently, to wind speed. The stronger the wind speed, the larger the horizontal gauge catch is in proportion to the operational gauge catch. Therefore, a correlation perhaps exists between wind-induced error and the precipitation amount caught by the horizontal gauge. Through field intercomparison tests, our aim is to derive a simple operational correction method for precipitation wind-induced error using a horizontal gauge catch, for which no additional measurements of the relevant meteorological variables, such as wind speed, precipitation intensity, temperature etc., are needed. It is assumed that the angle of precipitation approaching the gauge is a function of precipitation intensity, precipitation type, and wind speed.

2. Evaluation stations and intercomparison observations

Thirty precipitation evaluation stations were set up in different climate and altitude regions (Fig. 2). These stations were widely spread from latitude (20°02′–47°26′N) and from longitude (81°20′–126°58′E), and are situated at a diverse range of altitudes, the lowest being 4.8 m and the highest 3837 m. Differences in mean annual air temperature, mean annual wind speed and mean annual precipitation amount at the 30 stations are quite large.

There is one pit gauge, two operational gauges and one horizontal gauge installed at each evaluation station, and each gauge is aligned at intervals of 5–7 m. Figure 3 shows an example of an intercomparison site. The orifice areas of all precipitation gauges used in the field intercomparisons are 314 cm^2. The orifice heights of the two operational gauges and that of the horizontal gauge are all 70 cm aboveground. An operational gauge in a pit, with its orifice level with the surrounding ground, was used. Anti-splash grid of pit gauge is designed according to that WMO did (Goodison et al., 1998). The precipitation measurements in the pit can be used as a reference. The precipitation amounts in the above four gauges were measured manually once per precipitation event with a resolution of 0.1 mm.

Due to the spatial variation of the distribution of precipitation, the sample error will differ from site to site, plus there are random errors. The difference in precipitation amounts caught by two identical operational gauges with the same installation height is taken as random error, particularly given the precipitation spatial variation. The precipitation amount collected by the pit gauge is taken as a reference value without wind-induced error, the average value of those collected by the two operational gauges as an operational one, that collected by the horizontal gauge as the one

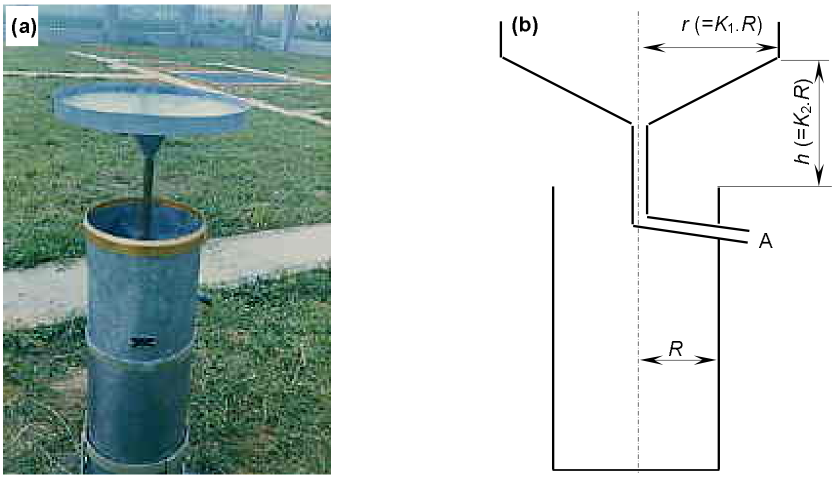

Fig. 1. Horizontal precipitation gauge as used during Chinese precipitation intercomparison measurements: (a) picture of horizontal precipitation gauge; (b) design chart of horizontal precipitation gauge. R is the radius of the operational gauge orifice (10 cm), and position A is the waterspout. K_1=1.5; K_2 =1.73.

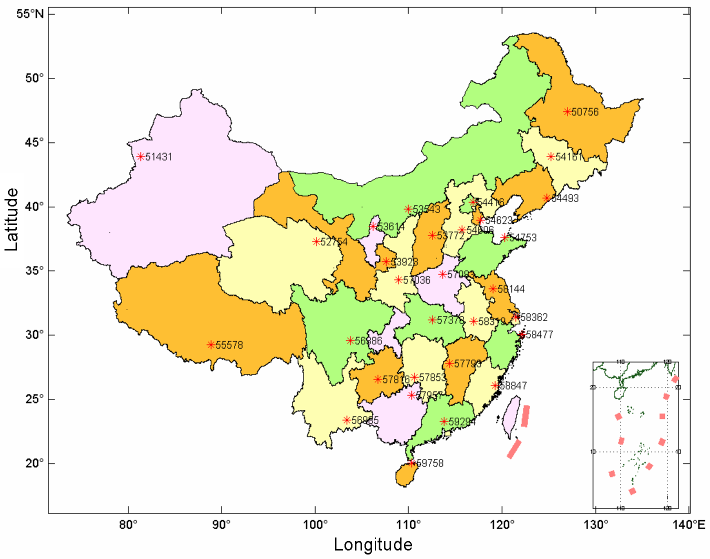

Fig. 2. Geographical distribution of the 30 evaluation stations (asterisks). The number near each asterisk refers to the station number.

used to correct the operational precipitation amount, and the difference between the operational precipitation amount and the reference value as the wind-induced error.

When there is blowing or drifting snow, precipitation collected by the pit gauge would be affected the most, and would thus be a faulty value. This must be eliminated when generating the statistics, as should the false values caused by manual operations, or other reasons. The number of field tests are presented in Table 1.

3. Precipitation measurement errors

3.1 *Random error*

In the intercomparison measurements, two identical operational gauges were installed at each evaluation station to measure the random error, especially that caused by the differences in spatial distribution of the precipitation amount. 26260 intercomparison

Table 1. Number of precipitation events measured, eliminated, and the effective number of events and days measured for rain and snow respectively during the intercomparison period at the 30 evaluation stations.

Number of events measured	Number of events eliminated	Effective number of events measured		Effective number of days measured	
		Rain	Snow	Rain	Snow
29276	784	26260	2232	16319	1665

Fig. 3. Picture of an evaluation station. Note that there are two operational gauges located at two sides of the horizontal gauge in the middle part of the picture and a pit gauge at the surface in front of them.

measurement events for rain were obtained, for which the random error more than 1.0 mm was 2.15%, and 2232 events for snow were obtained, for which the random error more than 1.0 mm was 1.21%. For around 45% of the precipitation events, the random errors were not equal to 0.0 mm; namely, the absolute values of the random errors were more than or equal to 0.1 mm in the intercomparison measurements of 0.1-mm resolution. Whether for rain or snow, the standard deviation of random error was 0.08 mm, and its average was 0.00 mm. There were enough samples such that the random errors of the above intercomparison observations fell very close to the Gaussian distribution for both rain and snow, as shown by dashed lines in Fig. 4.

3.2 *Systematic error*

3.2.1 *Wind-induced error*

The physical causes of wind-induced error have been confirmed by wind tunnel experiments (Sevruk and Klemm, 1989). The amount of precipitation caught by an elevated gauge is generally smaller than the amount of incident precipitation, and the loss of measured precipitation enhances as the proportion of small drops and light snow particles gets larger and the wind speed increases. Only a gauge with its orifice level equal to surface level, such as a pit gauge, will be free of wind-induced error.

Taking no account of wind-effect on the wetting amount of operational gauges per measurement event, we took the difference between the mean precipitation amount caught by the two operational gauges and that caught by the pit gauge as wind-induced error. 26260 effective observations for rain and 2232 effective observations for snow were obtained in the intercomparison measurements at the 30 stations. The mean wind-induced error was 0.19 mm for rain and 0.32 mm for snow per observation, and the standard deviation was 0.41 mm for rain and 0.52 mm for snow, respectively. The total precipitation amounts caught by the pit gauges and by the operational gauges in the 30 stations were 157810.7 mm and 152115.6 mm, respectively, and the mean relative wind-induced error was −3.6%. The distribution curves of absolute wind-induced errors for rain and snow in the measurements are given in Fig. 4 (solid lines). Whether for rain or snow, we can see that the wind-induced error distribution zone is obviously inclined to the left of the vertical axis where error is zero. This shows that the value measured by the operational gauge was

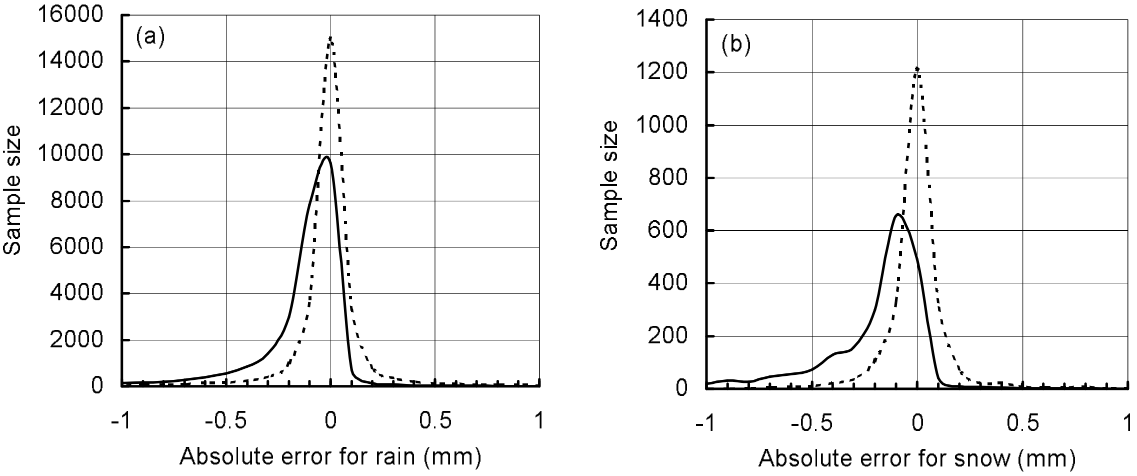

Fig. 4. Frequency distributions of random error (dashed lines) and wind-induced error (solid lines) in (a) rainfall and (b) snowfall measurements.

Table 2. Wetting loss of gauges per observation in Chinese stations (mm).

Station Number	54753	53772	54606	54623	57083	53947	56386	Mean
Collector	0.098	0.143	0.130	0.090	0.098	0.080	0.103	0.106
Container	0.036	0.097	0.110	0.090	0.075	0.075	0.107	0.084
Total	0.134	0.240	0.240	0.180	0.173	0.155	0.210	0.190

less than by the pit gauge. The distribution zone for snow is inclined to the left in Fig. 4, more than for rain, indicating that the wind-induced error for snow was greater than for rain. As we know, a resolution of 0.1 mm for precipitation measurement is very poor for analyzing precipitation measurement errors. If the initial difference lies between -0.05 to 0.05 mm, the difference should be classified as 0.0 mm. In a large proportion of precipitation events, the precipitation amount is small. Generally, the smaller the precipitation amount, the smaller the wind-induced absolute error. In addition, when the wind speed is very low, especially close to 0 m s^{-1}, the precipitation measurement does not obviously suffer from wind-field deformation. Therefore, certain numbers of precipitation events with no wind-induced error exist in Fig. 4. As the wind-induced error of precipitation is obtained by intercomparison measurements, the random error, especially due to differences in the spatial distribution of precipitation amounts, exists in each measurement; although it could be eliminated by accumulative total, it could not be eliminated in each observation. Hence the random errors have some effect on the frequency distribution statistics of wind-induced error at 0.1 mm intervals; subsequently, there are some events with positive differences for wind-induced error (Fig. 4), as some random errors are larger than the initial wind-induced errors.

3.2.2 *Wetting loss*

Wetting loss is another cumulative systematic loss from manual gauges which varies with precipitation and gauge type. Its magnitude is also a function of the number of times the gauge is emptied (WMO, 1996). In China, precipitation is measured generally every six hours at weather stations, but every 12 hours at other stations. The wetting loss of the operational precipitation gauge was also measured in seven stations in China (Table 2). The mean wetting loss of the collector and container was about 0.1 mm per rainfall event if they were sufficiently wetted. The wetting loss of the Chinese operational gauges was about 0.2 mm per rainfall event.

3.2.3 *Evaporation loss and splashing loss*

Operational gauges in China are always designed to prevent evaporation loss and to prevent rain from splashing in and out. The rim of the collector has a sharp edge and falls away vertically inside, steeply beveled on the outside. The collector has a vertical wall sufficiently deep and a slope of the funnel sufficiently steep to prevent rain from splashing in and out. The gauge with a funnel can keep the rain collected in the container closely sealed. The evaporation loss for rain was measured from 1000 to 1600 LST at three stations in the summer and autumn. The result was that evaporation loss for rain was much less than 0.1 mm.

Table 3. Statistics of the mean wind-induced error and sample size according to each certain class of precipitation amount caught by the horizontal gauges.

Classes of X (mm)	Measured values				Daily values			
	Rain		Snow		Rain		Snow	
	Y (mm)	N	Y (mm)	N	Y (mm)	N	Y (mm)	N
⩽0.1	0.06	12148	0.07	628	0.08	5591	0.09	386
0.1–0.2	0.11	3359	0.12	320	0.14	1811	0.13	193
0.2–0.3	0.15	1880	0.18	191	0.19	1160	0.18	124
0.3–0.4	0.19	1179	0.20	127	0.23	873	0.23	99
0.4–0.5	0.22	813	0.24	110	0.28	632	0.26	71
0.5–0.6	0.24	630	0.35	89	0.29	481	0.29	68
0.6–0.7	0.22	523	0.36	66	0.28	410	0.45	49
0.7–0.8	0.25	430	0.39	64	0.31	350	0.42	54
0.8–0.9	0.28	375	0.45	37	0.36	322	0.43	35
0.9–1.0	0.27	322	0.40	32	0.34	302	0.66	33
1.0–1.5	0.33	1071	0.48	166	0.39	939	0.54	146
1.5–2.0	0.35	721	0.50	96	0.44	650	0.56	90
2.0–2.5	0.42	488	0.70	69	0.51	449	0.77	68
2.5–3.0	0.47	368	0.79	54	0.54	340	1.03	46
3.0–3.5	0.61	269	0.66	36	0.71	262	0.93	34
3.5–4.0	0.63	223	0.89	36	0.68	224	0.90	39
4.0–4.5	0.71	182	1.19	23	0.88	187	1.35	24
4.5–5.0	0.68	163	1.13	15	0.77	160	1.39	15
5.0–6.0	0.68	215	1.58	17	0.76	225	1.51	26
6.0–7.0	0.74	175	1.16	17	0.88	186	1.16	16
7.0–8.0	0.97	148	1.70	11	1.05	133	1.48	14
8.0–9.0	0.94	93	1.84	5	1.03	105	1.78	7
9.0–10.0	0.90	66	1.07	3	0.93	61	1.37	5
10.0–11.0	1.03	64	2.02	5	1.25	74	2.13	6
11.0–12.0	1.34	42	2.09	4	1.12	36	2.20	5
12.0–13.0	0.91	49	1.52	3	1.04	49	1.61	4
13.0–14.0	1.31	36	/	0	1.49	48	/	0
14.0–15.0	1.55	26	2.42	3	2.13	25	2.42	3
15.0–20.0	1.37	86	/	0	1.44	104	/	0
20.0–25.0	1.21	47	2.84	5	1.57	55	2.84	5
25.0–30.0	2.08	31	/	0	1.84	32	/	0
30.0–40.0	2.33	22	/	0	2.48	22	/	0
40.0–50.0	2.64	9	/	0	3.06	12	/	0
50.0–100.0	4.35	6	/	0	4.49	7	/	0
> 100.0	2.00	1	/	0	3.80	2	/	0

X=precipitation amount caught by the horizontal gauge; Y=mean wind-induced error according to the range of X; N=sample size according to the range of X; "/"=no data.

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.

4. Correction of wind-induced error

4.1 *Relationship between wind-induced error and precipitation amount caught by the horizontal gauge*

To discover the relationship between wind-induced error and the precipitation amount caught by the horizontal gauge, and simultaneously to eliminate the impact of random errors, the wind-induced error (the difference in precipitation amount from the operational gauges and the pit gauges) were subdivided into 35 classes according to the precipitation amount caught by the horizontal gauges (Table 3). The interval between the classes could not be divided too short or too long; this should be based on the size of the original samples at each interval. In each interval, the greater the size of the original samples and the greater the number of intervals, the better the relationship can reflect the reality. Because rain and snow are different

Table 4. Statistical results of $Y = AX^B$.

	Measured values				Daily values			
	A	B	N	r	A	B	N	r
Rain	0.30	0.55	34	0.99	0.37	0.51	34	0.99
Snow	0.43	0.62	24	0.99	0.47	0.60	26	0.99

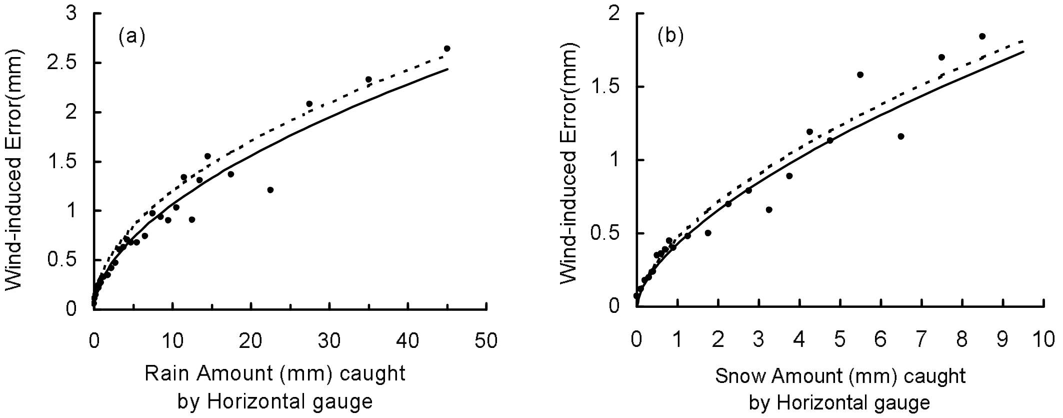

Fig. 5. Experimental relationship between wind-induced error and precipitation catch of the horizontal gauge: (a) rain; (b) snow. Dots are class averages of measured values from Table 3; solid lines are optimum fitting curves of measured values; and dashed lines are optimum fitting curves of daily values.

types of precipitation, statistics for these should be carried out separately, as they should for daily and event statistics.

As seen in the statistical results, whether for rain or snow, for the measured values or daily values the wind-induced error is obviously a univariate function of the precipitation amount caught by the horizontal gauge. Among various related statistics of univariate functions, the following power function equation possesses the highest correlation coefficient:

$$Y = AX^B \tag{1}$$

where Y is the wind-induced error, X is the precipitation amount caught by the horizontal gauge, A is the adjusted factor, and B is the index.

Table 4 lists factor A, index B, number (N) of classes, including not less than five intercomparison samples in the above correlation statistics, and the correlation coefficient r for gauges with an orifice area of 314 cm^2 and an installation height of 70 cm. Figure 5 shows the related curve of Eq. (1) and the class averages of measured values from Table 3. Values A and B of different gauge orifice sizes and different installation heights should be further confirmed by field intercomparison observations.

The wind-induced error is close to a power function of the precipitation amount caught by the horizontal gauge. The correlation coefficient is 0.99. The slope of the related curve of snow is larger than that of rain, thus they must be corrected with different coefficients. From the statistical result of measured values and daily values, two groups of related curves are approximately approaching (Fig. 5), and therefore we could actually make a correction of measured data or daily data as well. The correction procedure for wind-induced error is simple and convenient.

4.2 *Wind-induced error correction result in terms of Equation (1)*

Based on Eq. (1), all the measured data and daily data of the operational gauges have been corrected using precipitation caught by the horizontal gauges at the 30 stations. Comparing the corrected data with the pit catch, the distribution curve of relative wind-induced error after correction was obtained. Easy to compare, the distribution curve of relative wind-induced error before correction and that of relative random error measured by two operational gauges are also provided (Fig. 6). To avoid the influence of reading error and random error on low precipitation, we did not count the relative error of precipitation where the pit catch was less than 5.0 mm. From Fig. 6, it can be seen that the distribution curve of relative random error is nearly symmetrical about its vertical axis where the error is zero. The relative wind-induced error distribution zone before correction obviously lies

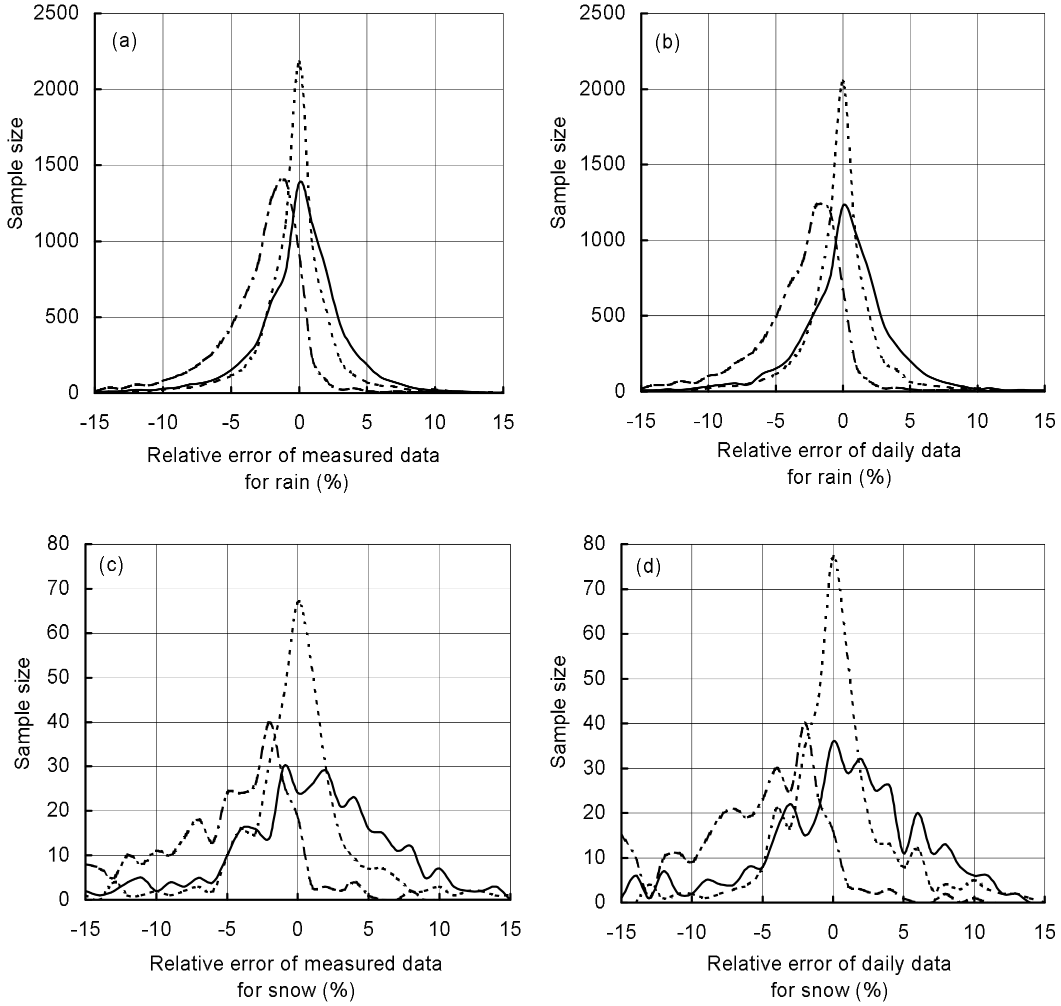

Fig. 6. Frequency diagram of relative error of (a) measured data for rain, (b) daily data for rain, (c) measured data for snow, and (d) daily data for snow. Each dot-dashed line shows the relative wind-induced error before correction, solid line shows after correction, and dashed line shows the relative random error.

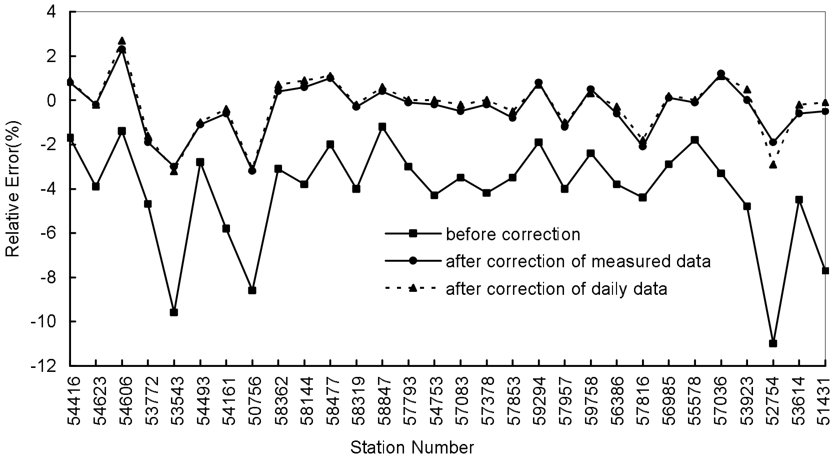

Fig. 7. Mean relative wind-induced errors of precipitation before and after correction.

on the left of its vertical axis, showing that the measured value by the pit gauge is more than that of the operational gauge. It can also be seen that each relative wind-induced error after correction is distributed on both sides of its vertical axis and is similar to the distribution of random error, showing a symmetrical distribution in accordance with random error and proving the effectiveness of correction. The correction of measured data and daily data has no obvious difference in Fig. 6.

The mean wind-induced error at the 30 stations was −2.5% for rain and −7.7% for snow before correction, and 0.2% for rain and 0.7% for snow after correction through Eq. (1). The error after correction is one order of magnitude less than that before correction. The mean wind-induced error of precipitation including both rain and snow was −3.6% before correction and 0.2% after correction through Eq. (1). The precipitation accuracy after correction approaches that of pit gauge. There is a variety of differences in wind-induced error between stations. Figure 7 shows each station's mean relative wind-induced error of precipitation before and after correction through Eq. (1). The mean wind-induced error of precipitation varies from −11.0% to −1.2% from station to station before correction, and after correction through Eq. (1) it oscillates around the line of 0% error rather than inclining to the underside of the line. That both curves of mean wind-induced error of measured values and daily values after correction are nearly in superposition shows that the correction of wind-induced error of measured data and daily data has the same effectiveness.

5. Correction of precipitation measurements

In China, evaporation loss and splashing loss are both close to 0.0 mm, and the wetting loss is around 0.2 mm per measurement if the inner walls of the collector and the container are both sufficiently wetted. The extent of wetting loss per measurement is in fact related to how much of the inner wall of the container has been wetted by rain and how much by melted snow. If a horizontal gauge is installed at the same site as an operational gauge, the wind-induced error can be corrected through Eq. (1). Leaving other errors alone, the adjusting equation for precipitation measurement can be given as follows:

$$P = P_{\mathrm{O}} + A \cdot X^{B} + C \qquad (2)$$

where P is the adjusted precipitation amount, P_{O} is the measured amount of precipitation in the operational gauge, X is the measured amount of precipitation in the horizontal gauge, C is the wetting loss amount, and A and B are the values as listed in Table 4.

6. Summary and conclusions

In China, for the operational gauge whose receiving orifice area is 314 cm^2 and installation height is 70 cm, the wetting error is 0.2 mm if the inner walls of the collector and container are wetted sufficiently and both evaporation error and splashing error are around 0.0 mm for each event; the random error is 0.0 mm for even measurement; and the mean wind-induced error is 0.19 mm and 0.32 mm for rain and snow events, respectively. The correction for Chinese precipitation measurements is mainly centered around the correction of wind-induced error and wetting loss.

Comparing around 28 000 events between measurements made by pit gauges, operational gauges and horizontal gauges, the power function correlation between the precipitation catch of the horizontal gauge and absolute difference of precipitation catches of the operational gauge and the pit gauge was confirmed in the statistics of measured values and daily values. The correlation curve of measured events is similar to that of daily events. The difference between the two curves is small. The slope of the curve for snow is larger than that for rain. The correlation coefficient is above 0.99. The relationship has been built in different climate, regime and geographical conditions, and thus is greatly representative.

The mean wind-induced error at 30 stations was −2.5% for rain and −7.7% for snow before correction, and 0.2% for rain and 0.7% for snow after correction through Eq. (1). The error after correction was one order of magnitude less than that before correction. The mean wind-induced error of precipitation including both rain and snow was −3.6% before correction and 0.2% after correction. The adjusted wind-induced error distribution was similar to the distribution of random error.

For operational observations, the correction of wind-induced error of measured values and daily values can only be carried out by parallel observations with a horizontal gauge, which is as simple as an operational gauge to use. The correction procedure is simple and feasible. This method is very suitable for correcting point precipitation (rain or snow) measurements of routine observations.

Acknowledgements. This work was supported by the China Meteorological Administration (sponsored program: 98-2W–2/2013). We would like to thank Mr. Zhang Hongzheng for helping to draw Fig. 2 in the paper and many station observers for their work contributing to the development of the program. We also thank Mr. Zhou

Shijian for his help in improving the manuscript.

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