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Precipitation measurement biases in an arid setting of central Asia: using different methods to divide precipitation types

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ABSTRACT: Accurate precipitation data play important roles in climate and hydrology research at regional and global scales. The correction of system errors associated with precipitation represents a feasible and effective way to improve the accuracy of rainfall data. We analysed and corrected rainfall data collected at 45 meteorological sites in Xinjiang over 55 years (from 1 January 1960 to 31 December 2014) in terms of the wetting loss, trace precipitation and wind-induced loss, with 2 judgement methods of precipitation types. We based our analysis on daily temperature, wind speed, precipitation, relative humidity and air pressure data. Precipitation after correction was compared to precipitation before correction. The primary conclusions are: (1) Based on the new method of distinguishing precipitation types, the results show more snow days, fewer mixed precipitation days and slightly fewer rain days than the traditional method. (2) The sum values of corrections for each loss based on the new method of distinguishing precipitation types are higher than those based on the traditional method in spring and autumn. The sum values of corrections and differences of each loss are all larger in North Xinjiang and smaller in South Xinjiang. The sum values of total corrections are larger on the north slope of the Tianshan Mountains and smaller on the south slope, and they decrease from the south slope to South Xinjiang. (3) The median values of the sum of each loss and total correction in the northern region of Xinjiang are higher than those in the central region of Xinjiang, which are higher than those in the southern region of Xinjiang on the whole. (4) Precipitation increases after correction. The annual mean corrected values at Bayanbulak (in the Tianshan Mountains), Altay (in North Xinjiang) and Yutian (in South Xinjiang) are 81.48, 54.60 and 12.55 mm, respectively.

KEY WORDS: Precipitation observation · Bias correction · Precipitation type · Xinjiang

1. INTRODUCTION

Precipitation is essential meteorological information. Reliable precipitation climatology and descriptions of long-term mean values and variations at regional and global scales are critical for hydro-thermal circulation and climate change research (Lv et al. 2011, Xiong et al. 2011). Improvement of the accuracy of precipitation data is essential to accurately address relevant scientific problems in climatology and hydrology (Lv et al. 2011).

Precipitation data are generally based on measurements using precipitation gauges. However, many inaccuracies have been confirmed in these records. Yang et al. (1988) found that precipitation measured by rain gauges was generally less than actual rainfall. Other studies have indicated that precipitation records are often incompatible in studies across na-

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tional borders (Legates 1995, Karl et al. 1993, Yang et al. 2001). Uncertainty can affect studies of hydrological processes and climate change because of the inaccuracy of rainfall records (Yang et al. 2004, Tian et al. 2007, Ye et al. 2008, Wang et al. 2012); thus, it is important to analyse the uncertainty associated with rainfall gauge records (Walsh et al. 1998). Uncertainty primarily comes from 3 sources: (1) the uneven distribution of meteorological stations, (2) different types of precipitation gauges with different installation and observation methods, and (3) the influence of system errors in precipitation observation processes, such as wind-induced loss, wetting loss, and trace precipitation (Yang et al. 1999b, Ye et al. 2004, 2007). Among the 3 error sources, correcting the system errors in precipitation observation processes is a feasible and effective way to improve the accuracy of rainfall data.

Research on rainfall observation errors started in the 1980s. The World Meteorological Organization (WMO) launched the International Solid Rainfall Observation Project in 1985 (Goodison et al. 1989), in which a series of comparative experiments were performed in 20 observation fields in 13 countries from 1986 to 1993 to analyse the system errors in rain gauges (Goodison et al. 1998). The WMO has since improved the correction methods of system errors in commonly used rainfall observation instruments throughout the world (Gunther 1993, Allerup et al. 1997, Yang et al. 1999a); for instance, the Nipher snow gauge of Canada (Goodison & Metcalfe 1992), the 8′ standard rain gauge of the United States (Yang et al. 1998b), and the Tretyakov and Hellmann rain gauges of Russia (Yang et al. 1995). These methods mainly address system errors on a daily scale using meteorological data such as wind speed, temperature, and precipitation type. The methods have been widely applied in different countries and regions, such as Greenland (Yang et al. 1999b), Mongolia (Zhang et al. 2004), Siberia (Yang & Ohata 2001), Alaska (Yang et al. 1998a), and the high latitudes north of 45° N (Yang et al. 2005). The results of these studies showed that revised rainfall increased significantly compared to the original observed precipitation (Metcalfe et al. 1994, Yang et al. 1998b, Yang 1999). Additionally, the amount of global precipitation increased by 11% after the correction (Legates & Willmott 1990). Overall, the system errors (including wetting loss, wind-induced loss, trace precipitation, and evaporation loss) of different rain gauges (except for the Chinese standard rain gauge) in different countries have become increasingly clear in recent years. Additionally, the correction methods for system errors have been widely applied in different countries and regions. Thus, the accuracy of the precipitation data has been greatly improved. However, international precipitation gauges exhibit significant differences based on the types of gauges, installation standards, and observation methods used in different countries. Thus, the methods of system error correction suitable for precipitation gauges in other countries do not fit the Chinese Standard Precipitation Gauge (CSPG).

The CSPG has been widely used in Chinese weather stations for liquid and solid precipitation observations since the 1950s (China Meteorological Administration 2003). From 1985 to 1991, numerous experiments were conducted in the Urumqi River Basin (Northwest China) to study the systematic errors in Chinese gauge measurements. The elevations of meteorological stations in these experiments range between 917 m (Urumqi Station) and 3730 m (Terminal of the Urumqi Glacier No. 1). Additionally, most of the climate conditions that influenced rainfall observation errors were taken into account, and precipitation bias correction methods suitable for CSPGs were developed (Yang et al. 1991, Goodison & Metcalfe 1992, Sevruk et al. 2009). Moreover, the China Meteorological Administration also conducted experiments lasting 7 yr and nearly 12 successive months to explore methods of system error correction for CSPGs (Ren et al. 2003, 2007). Zhao et al. (2014) summarized the correction formulas for liquid, solid, and mixed precipitation as observed by the Geoner T-200B. These correction methods have played an important role in the revision of rainfall observation errors in Chinese meteorological data (Ding et al. 2007, Ren & Li 2007, Ye et al. 2004, 2008). Ye et al. (2007) corrected the system errors in precipitation data collected at 726 weather stations in China from 1951 to 2004. Other relevant domestic studies primarily concentrated on the Dongkemadi River Basin in the Tanggula Mountains (located in the middle of the Tibetan Plateau) (He et al. 2009), North China (Sun et al. 2013), Northeast China (Sun 2012), and the Qilian Mountains (located northeast of the Tibetan Plateau) (Chen et al. 2015).

The correction methods proposed by the WMO have been applied in different regions of China, and suitable correction methods have been developed for some specific areas of China. The differences between Chinese rainfall measurement methods and those of other countries were compared and analysed, and the accuracy of precipitation data in China was effectively improved. Additionally, the system error was analysed quantitatively, and the temporal and spatial variations of the corrections were elucidated to some extent.

The terrain and climate in Xinjiang are very complex (Zhang & Zhang 2006, Yuan & Yang 1990). The influence of precipitation observation errors on the accuracy of rainfall data in Xinjiang cannot be ignored (Yang et al. 1991, Goodison & Metcalfe 1992). The error correction methods proposed from a series of observation experiments organized by the WMO in the Urumqi River Basin, China, show reliable veracity in Northwest China (including Xinjiang). The accuracy of distinguishing different precipitation types (rain, snow, and mixed) is essential to ensure that the errors in precipitation data can be effectively corrected. However, precipitation types were not recorded in long-term meteorological data sets after 1979. Most previous studies used air temperature-based methods, e.g. −2°C and 2°C (Zhang et al. 2004, Ye et al. 2007) to identify different precipitation types. This temperature-based method may increase the uncertainty of the correction because of the obvious variations of climate conditions in the study area (Yang et al. 1998b, Fassnacht et al. 2001, Fassnacht 2004, He et al. 2009). Ding et al. (2014) proposed a parameterized scheme to determine precipitation types, and the accuracy of the new scheme is better than the other schemes applied in land surface and hydrological models (Loth et al. 1993, Wigmosta et al. 1994, Yang et al. 1997, Hock & Holmgren 2005, Wang et al. 2011).

In this study, based on 2 methods (the new parameterized scheme and the dual-threshold method using −2°C and 2°C) (Ding et al. 2014, Ye et al. 2007) of dividing different precipitation types, 55 yr (from 1 January 1960 to 31 December 2014) of precipitation data from 45 meteorological sites in Xinjiang are corrected and analysed in terms of the wetting loss, trace precipitation, and wind-induced loss. The precipitation types and the corrections of each loss are compared. The correction in North, Middle, and South Xinjiang and the precipitation before and after correction are also discussed. This information can significantly contribute to the understanding of precipitation observation errors in different regions of Xinjiang. Moreover, more accurately corrected rainfall data can be applied in hydrothermal models and climate change research.

2. STUDY AREA

Xinjiang is situated at the centre of the Eurasian continent in northwestern China. Xinjiang extends between 73° 20′ and 96° 25′ E and from 34° 15′ to 48° 10′ N, and covers an area of 1.67 × 10^6 km^2. Xinjiang is the province with the largest land area, longest border, and maximum number of neighbouring countries. The length of its border is ~5400 km (Zhang & Zhang 2006). A variety of external agents shape the diversity of landscape types in Xinjiang (Yuan & Yang 1990). Three mountain ranges (Altay Mountains, Kunlun Mountains, and Tianshan Mountains) and 2 basins (Tarim Basin and Junngar Basin) compose the topography of Xinjiang. Elevations range from >7000 m to lower than sea level. Generally speaking, the climate of Xinjiang is arid and semi-arid, and the local climates in different regions of Xinjiang are complex and diverse. The effects of precipitation observation errors on the accuracy of rainfall data in Xinjiang can not be ignored (Yang et al. 1991).

3. DATA AND METHODOLOGY

3.1. Meteorological data

The daily mean temperature (T_d), precipitation (P), wind speed (W_s), relative humidity (RH), and air pressure (p_s) data used in this study were provided by the Xinjiang Meteorological Bureau. The original data set contained 68 meteorological stations distributed across Xinjiang. The daily data from 19 meteorological stations that do not cover the period from 1 January 1960 to 31 December 2014 were removed. In addition, if the meteorological station is moved during the study period, the environmental background of the station will be changed, which can cause significant uncertainty in the records of meteorological elements. In the long-term climatology data sets, 2 types of meteorological record are provided by the China Meteorological Administration when the horizontal migration distance of a site is >50 km, or when the vertical migration distance of a site is >100 m. On this basis, the daily data from 4 meteorological stations (Urumqi, Shisanjianfang, Hongliuhe, and Wenquan) were removed. Finally, daily T_d, P, W_s, RH, and p_s data collected at 45 meteorological stations from 1 January 1960 to 31 December 2014 were used in this paper (Fig. 1). Seasonal monthly denominations were MAM, JJA, SON, and DJF for spring, summer, autumn and winter, respectively. During the data analysis, the daily records within a season were removed if the data were available for <80 d during the calculation of the seasonal mean value. Under this circumstance, the data of Yiwu from 2003 to 2006 were removed. Daily data for a year were removed if ≥1 seasons (in the 4 seasons) were missing during the calculation of the annual mean value.

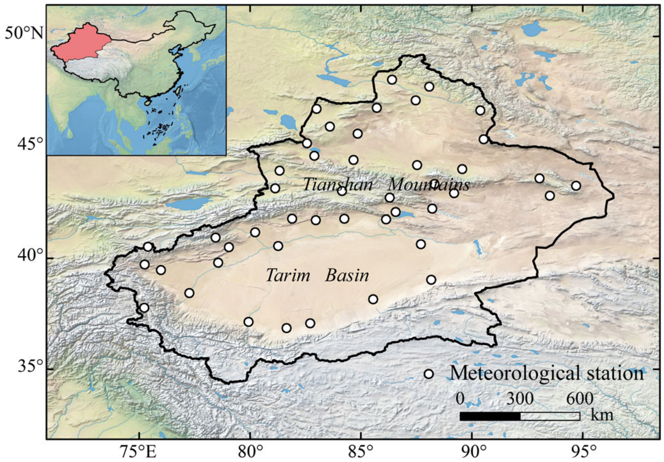

Fig. 1. Meteorological stations in Xinjiang used in this study

3.2. Determination of precipitation type

Distinguishing different precipitation types (rain, snow, and mixed) is essential to the correction of system errors. The correction methods for wetting loss and wind-induced loss vary with different precipitation types. The accuracy of the determination of precipitation type directly affects the accuracy of the correction results. The traditional method of determining the precipitation type was based on temperatures of −2.0°C and 2.0°C. Precipitation was defined as snow when the average temperature was <−2.0°C and as rain when the average temperature was >2.0°C. Mixed precipitation was assumed when the average temperature was between −2.0°C and 2.0°C (Zhang et al. 2004, Ye et al. 2007).

The details of the new scheme to determine the precipitation type (snow, rain, or mixed) developed by Ding et al. (2014) are as follows:

$$\text{type} = \begin{cases} \text{snow} & (T_w \le T_{\min}) \\ \text{mixed} & (T_{\min} < T_w < T_{\max}) \\ \text{rain} & (T_w \ge T_{\max}) \end{cases} \tag{1}$$

where T_w denotes the wet-bulb temperature (°C), T_{min} denotes the daily minimum temperature (°C), and T_{max} represents the daily maximum temperature (°C). T_w is deduced as follows:

$$T_w = T_d - \frac{e_{sat}(T_d)(1-\text{RH})}{0.000643 p_s + \dfrac{\partial e_{sat}}{\partial T_d}} \tag{2}$$

where T_d is the daily mean temperature (°C), RH is relative humidity (%), and p_s is the air pressure (hPa). Additionally, $e_{sat}(T_d)$ denotes the saturated vapour pressure (hPa) at T_d and can be calculated as follows (Murray 1967):

$$e_{sat}(T_d) = 6.1078 \exp\left(\frac{17.27 T_d}{T_d + 237.3}\right) \tag{3}$$

T_{min} and T_{max} can be defined as follows:

$$T_{\min} = \begin{cases} T_0 - \Delta S \times \ln\left[\exp(\frac{\Delta T}{\Delta S}) - 2\exp(-\frac{\Delta T}{\Delta S})\right] & \left(\frac{\Delta T}{\Delta S} > \ln 2\right) \\ T_0 & \left(\frac{\Delta T}{\Delta S} \le \ln 2\right) \end{cases} \tag{4}$$

$$T_{\max} = \begin{cases} 2T_0 - T_{\min} & \left(\frac{\Delta T}{\Delta S} > \ln 2\right) \\ T_0 & \left(\frac{\Delta T}{\Delta S} \le \ln 2\right) \end{cases} \tag{5}$$

The 3 parameters (ΔT, ΔS, and T_0) in these equations can be expressed as follows:

$$\Delta T = 0.215 - 0.099\text{RH} + 1.018\text{RH}^2 \tag{6}$$

$$\Delta S = 2.374 - 1.634\text{RH} \tag{7}$$

$$T_0 = -5.87 - 0.1042h + 0.0855h^2 + 16.06\text{RH} - 9.614\text{RH}^2 \tag{8}$$

In Eqs. (6–8), RH denotes relative humidity, which ranges between 0 and 1, and h is the elevation of the meteorological station (km).

3.3. Precipitation measurement bias correction methods

The primary system errors associated with precipitation measurement include that trace precipitation (<0.1 mm) cannot be measured via gauges, and the precipitation collected in gauges can evaporate prior to measurement. Additionally, rainfall that sticks to the inner wall of the gauge cannot be measured. Furthermore, the gauge collection ability is affected by the wind field above the gauge. Therefore, the correction includes 4 aspects: evaporation loss, wind-induced loss, wetting loss, and trace precipitation.

The total rainfall correction equation (Sevruk & Hamon 1984) is as follows:

$$P_c = K(P_m + \Delta P_w + \Delta P_e) + \Delta P_t \tag{9}$$

where P_c is the corrected precipitation (mm), and K is the correction coefficient of wind-induced loss. The value of K is generally >1. Additionally, P_m is measured precipitation (mm), ΔP_w is the wetting loss (mm), ΔP_e is the evaporation loss (mm), and ΔP_t is trace precipitation (mm).

3.3.1. Wetting loss. Wetting loss is the precipitation that is retained or sticks to the gauge but is not measured, and it is closely associated with the precipitation type and time of measurement (Yang et al. 1988, Ye et al. 2004, 2007). A series of experiments performed in the Urumqi River Basin showed that wetting loss varied with different precipitation types (Ding et al. 2007, Ye et al. 2008). During one precipitation event, the average value of wetting loss was 0.30 mm for snow, 0.23 mm for rain, and 0.29 mm for mixed precipitation (Yang et al. 1991). According to the rainfall observation standards of China, precipitation observations are taken twice a day. Although precipitation correction is performed on a daily basis, precipitation may not be continuous over an entire day. Therefore, one precipitation observation process is considered, and the minimum wetting loss correction is analysed for a rainy day in this paper.

3.3.2. Trace precipitation. Precipitation <0.1 mm exceeds the resolution of CSPGs, and it is normally considered a trace precipitation event (Ye et al. 2004). In the official precipitation records of Chinese meteorological stations, trace precipitation is considered a zero value quantitatively, and a day when a trace precipitation event occurs is labelled a trace precipitation day. Based on the climate data from 45 meteorological stations in Xinjiang from 1 January 1960 to 31 December 2014, the seasonal mean number of trace precipitation days ranges from 8.75 to 19.50 d (Table 1). The number of trace precipitation days accounts for >50% of the sum of the trace precipitation days and the measurable precipitation days in all 4 seasons (Table 1). As shown, trace precipitation accounts for a large proportion of the precipitation in Xinjiang; thus, the correction of trace precipitation cannot be ignored. In a single trace precipitation day, 2 or more trace precipitation events may be reported, and the amounts may range from 0.05 mm to 0.15 mm (Ye et al. 2004). In this study, trace precipitation is corrected on a daily basis, and for each trace precipitation day a rainfall amount of 0.1 mm, a conservative value, is added to the monthly total rainfall.

3.3.3. Evaporation loss. Evaporation loss is rainfall that evaporates from the gauge before measurement. Based on a comprehensive assessment during the WMO intercomparison project, the average value of daily evaporation loss varies with gauge type and season (Aaltonen et al. 1993, Goodison et al. 1998). The design of CSPGs has reduced the evaporation loss to a large extent. Evaporation loss is less significant than the other 3 types of losses due to the use of a funnel and container, even in the rainy, warm season in arid areas (with high potential evaporation) (Ye et al. 2004). Evaporation loss is also small in winter according to studies in Mongolia (Zhang et al. 2004) and Finland (Aaltonen et al. 1993). In addition, evaporation loss is highly dependent on weather conditions and observation methods (Yang et al. 1999a). Daily evaporation loss displays distinct variations at different meteorological stations. Thus, it is unreasonable to assume a certain value as the average evaporation loss at every meteorological station throughout the year. Additionally, previous studies (Yang et al. 1999a, Ye et al. 2004) have shown that ignoring the evaporation loss will not significantly affect the bias correction results. Therefore, evaporation loss was not corrected in this study.

Table 1. Seasonal and annual mean values of trace precipitation days, the sum of trace and measurable precipitation days, and the proportion of trace precipitation days for all the 45 stations in Xinjiang from 1 January 1960 to 31 December 2014

	Trace precipitation days (d)	Sum days (d)	Proportion (%)
Spring	11.59	24.25	53.13
Summer	19.5	40.37	50.78
Autumn	8.75	19.52	50.61
Winter	11.36	23.39	51.97
Annual	51.2	107.54	51.43

3.3.4. Wind-induced loss. Previous studies have indicated that the most significant variable that influences the catch efficiency of a precipitation gauge is the wind speed during the rainfall period (Yang et al. 1995, Goodison et al. 1998). Wind-induced loss comes from the deformation of the wind field above a precipitation gauge (Sevruk & Hamon 1984). Some precipitation that falls close to the gauge deviates from the original track and cannot be caught and measured. In the WMO intercomparison project, the catch ratio was considered to be the proportion of the rainfall amount caught by the gauge (including measured precipitation and wetting loss) to the true precipitation amount (Goodison et al. 1998). The precipitation gauge catch ratios of different precipitation types (rain, snow, and mixed) are not identical. The catch ratio of rain is larger than that of snow because rainfall is less affected by wind than snowfall (Goodison et al. 1998, Yang et al. 1995). The catch ratio is also related to the wind speed above the gauge and the exposure extent of the gauge. Additionally, the catch ratio decreases as the wind speed increases over the gauge. Based on experiments performed in the Urumqi River Basin, the relationships between the snow, rain, and mixed precipitation catch ratios and wind speed were assessed for CSPGs (Yang et al. 1991). The precipitation types (snow, rain, and mixed precipitation) were also assessed using the parameterization scheme developed by Ding et al. (2014).

The catch ratios (CR,%) of different precipitation types are as follows:

$$CR_{snow} = 100\exp(-0.056W_s) \quad (0 < W_s < 6.2) \quad (10)$$

$$CR_{rain} = 100\exp(-0.041W_s) \quad (0 < W_s < 7.3) \quad (11)$$

$$CR_{mixed} = CR_{snow} - (CR_{snow} - CR_{rain})(T_{daily} + 2)/4 \quad (12)$$

where W_s denotes the wind speed (m s^{-1}) at the standard gauge height (10 m), and T_{daily} is the daily mean temperature (°C).

The correction coefficient (K,%) of wind-induced loss is calculated as follows:

$$K = \frac{1}{CR} \quad (13)$$

4. RESULTS

4.1. Comparison of precipitation types according to 2 methods

Total days (d) of different precipitation (snow, mixed, and rain) based on 2 precipitation type dividing methods in spring and autumn in Xinjiang from 1960 to 2014 are presented in Fig. 2. Method 1 is the new scheme proposed by Ding et al. (2014). Method 2 is the dual temperature threshold method (−2°C/2°C) (Zhang et al. 2004, Ye et al. 2007). In spring, the total number of snow days based on Method 1 exceeds those calculated using Method 2. Method 2 shows more mixed precipitation days and slightly more rain days compared with Method 1 at most meteorological stations. Similarly, Method 2 shows more snow days, fewer mixed precipitation days, and slightly fewer rain days compared to Method 1 in autumn. In the supplemental tables (Tables S1 & S2 in the Supplement at www.int-res.com/articles/suppl/c076p073_supp.pdf), the average snow, rain, and mixed precipitation days (d) based on the 2 methods of dividing different precipitation types at each meteorological station of Xinjiang in spring and autumn from 1960 to 2014 are shown in detail.

Table 2 shows the average precipitation days and total precipitation days of different precipitation types (snow, mixed, and rain) based on 2 precipitation type dividing methods in spring and autumn in Xinjiang from 1960 to 2014. Differences can be found easily in the 3 precipitation types determined by the 2 methods. The average number of precipitation days of snow in spring and autumn identified by the new scheme (Method 1) are 1.12 and 1.25 d, respectively, greater than those decided by the traditional dual temperature threshold method (−2°C/2°C) (Method 2). For mixed precipitation days, Method 1 identified 1.08 and 1.05 d fewer than Method 2 in spring and autumn, respectively. The differences in rain days were smaller compared to the snow and mixed precipitation days, with Method 1 identifying 0.27 and 0.18 d fewer in spring and autumn, respectively. In terms of the total precipitation days, similar characteristics can be found. Method 1 identified 94.85 d more total snow days and 79.13 d fewer total mixed precipitation days than Method 2 in spring. Method 1 defined 15.83 and 10.48 d fewer total rain days than Method 2 in spring and autumn, respectively, from 1960 to 2014.

4.2. Comparison of correction for each loss

In this study, the precipitation observation error was corrected on a daily basis. In the comparison of the corrections based on 2 methods of distinguishing different precipitation types, the sums of daily corrections of trace precipitation, wetting loss, and wind-induced loss and the sum of daily total corrections based on the new scheme (Method 1) were calculated. The sum of daily corrections for each loss based on Method 1 at each station minus that based on the dual temperature threshold method (Method 2, −2°C/2°C) at each station equals the difference for each loss correction. The same approach was used to calculate the difference for total correction.

Fig. 3 presents the sum of daily corrections (mm) for trace precipitation at each station in spring and autumn in Xinjiang from 1960 to 2014. Clear spatial variations can be observed in the bias correction of trace precipitation. The sum values of corrections in North Xinjiang are higher than those in South Xinjiang both in spring and autumn. The sum values of corrections on the north slope of the Tianshan Mountains are higher than those on the south slope in spring and autumn. The sum values of corrections display a decreasing trend from the south slope of the Tianshan Mountains to South Xinjiang in the 2 seasons. The sum values of corrections in spring are generally higher than those in autumn. In North Xinjiang, the sum values of corrections in spring are >55.0 mm, while some of those in autumn range between 45.0 and 55.0 mm. For South Xinjiang, the number of meteorological stations at which corrections are <35.0 mm in autumn is more than that in spring.

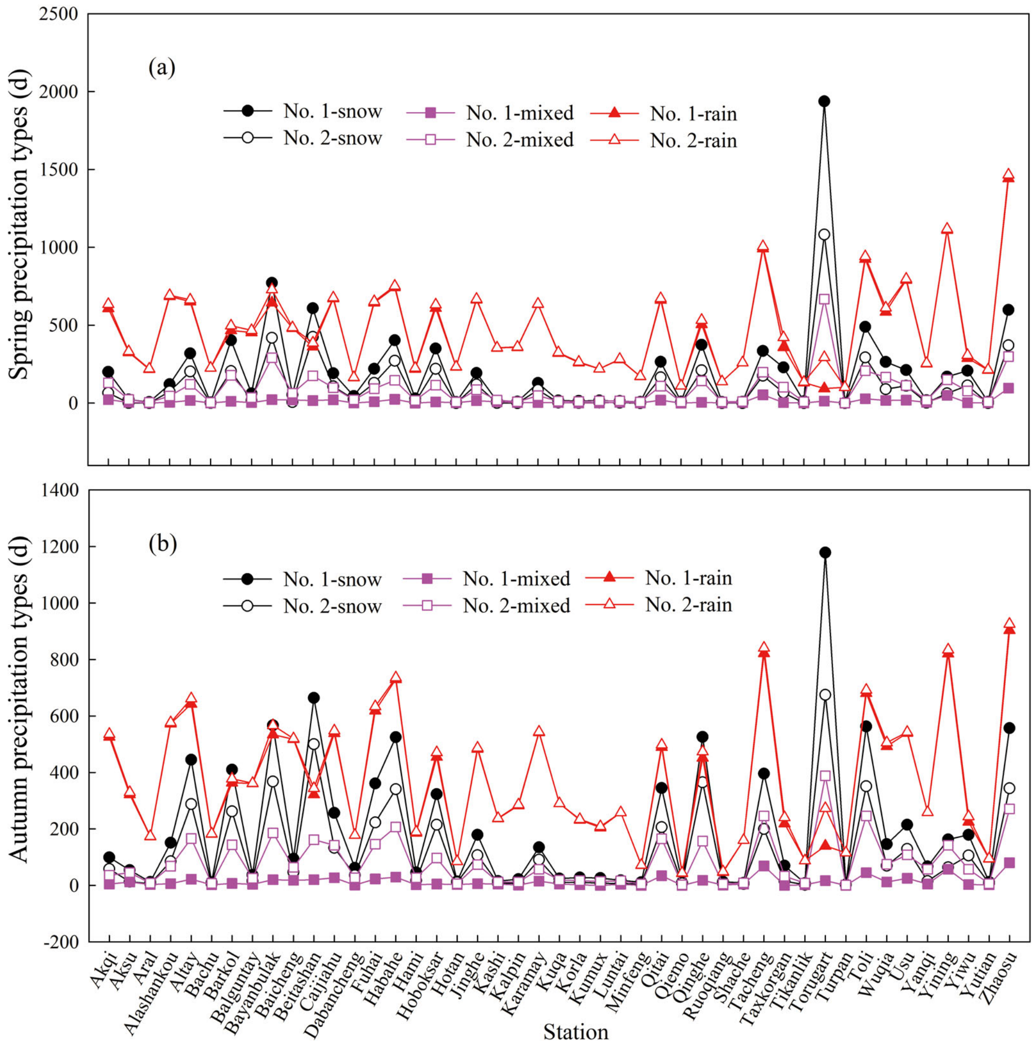

Fig. 2. Total days (d) of different precipitation types (snow, mixed and rain) based on the 2 precipitation type distinguishing methods (1. the new scheme; 2. the dual temperature threshold method, −2°C/2°C) in (a) spring and (b) autumn at each station in Xinjiang from 1960 to 2014

Table 2. Average precipitation days and total precipitation days of different precipitation types (snow, mixed and rain) based on 2 precipitation type dividing methods (1. the new scheme; 2. the dual temperature threshold method, −2°C/2°C) in spring and autumn in Xinjiang from 1960 to 2014

	Average precipitation days		Total precipitation days	
	New scheme (No. 1)	−2°/2°C (No. 2)	New scheme (No. 1)	−2°/2°C (No. 2)
Spring				
Snow	4.54	3.42	214. 11	119.26
Mixed	1.38	2.46	12.7	91.83
Rain	8.66	8.93	468.15	483.98
Autumn				
Snow	4.6	3.35	205.46	124.5
Mixed	1.26	2.31	14.28	84.98
Rain	6.99	7.17	371.8	382.28

Fig. 4 shows the sum of daily corrections (mm) for wetting loss (Fig. 4a,b) and the differences (Fig. 4c,d) resulting from the 2 methods of distinguishing different precipitation types in spring and autumn in Xinjiang from 1960 to 2014. The sum of daily wetting loss correction based on Method 1 at each station minus that based on Method 2 at each station equals the difference for wetting loss correction. The spatial variations can be seen easily. The sum values of corrections for wetting loss in North Xinjiang (both >150.0 mm) are higher than those in South Xinjiang (both ≤150.0 mm) in spring and autumn. The sum values of corrections for wetting loss on the north slope of the Tianshan Mountains are higher than those on the south slope in the 2 seasons. The values display a decreasing trend from the south slope of the Tianshan Mountains to South Xinjiang in spring and autumn. Additionally, the seasonal variations are small be-

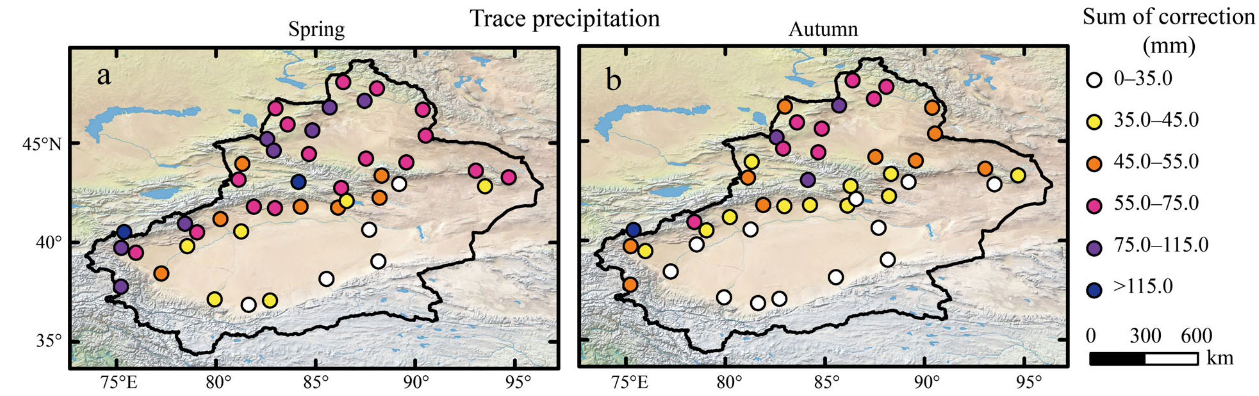

Fig. 3. Sum of daily corrections for trace precipitation at each station in (a) spring and (b) autumn in Xinjiang from 1960 to 2014

tween spring and autumn throughout Xinjiang. The sum values of corrections for wetting loss based on Method 1 are greater than those based on Method 2 at all the meteorological stations in spring and autumn. Greater differences in values appear in North Xinjiang and South Xinjiang has lower values in both seasons. The sum values of differences on the south slope of the Tianshan Mountains are lower than those on the north slope in spring and autumn.

Fig. 5 exhibits the sum of daily corrections (mm) for wind-induced loss (Fig. 5a,b) and the differences (Fig. 5c,d) resulting from the 2 methods of dividing different precipitation days in spring and autumn in Xinjiang from 1960 to 2014. The sum of daily wind-induced loss correction based on Method 1 at each station minus that based on Method 2 at each station equals the difference for wind-induced loss correction. The spatial characteristics are similar to the wet-

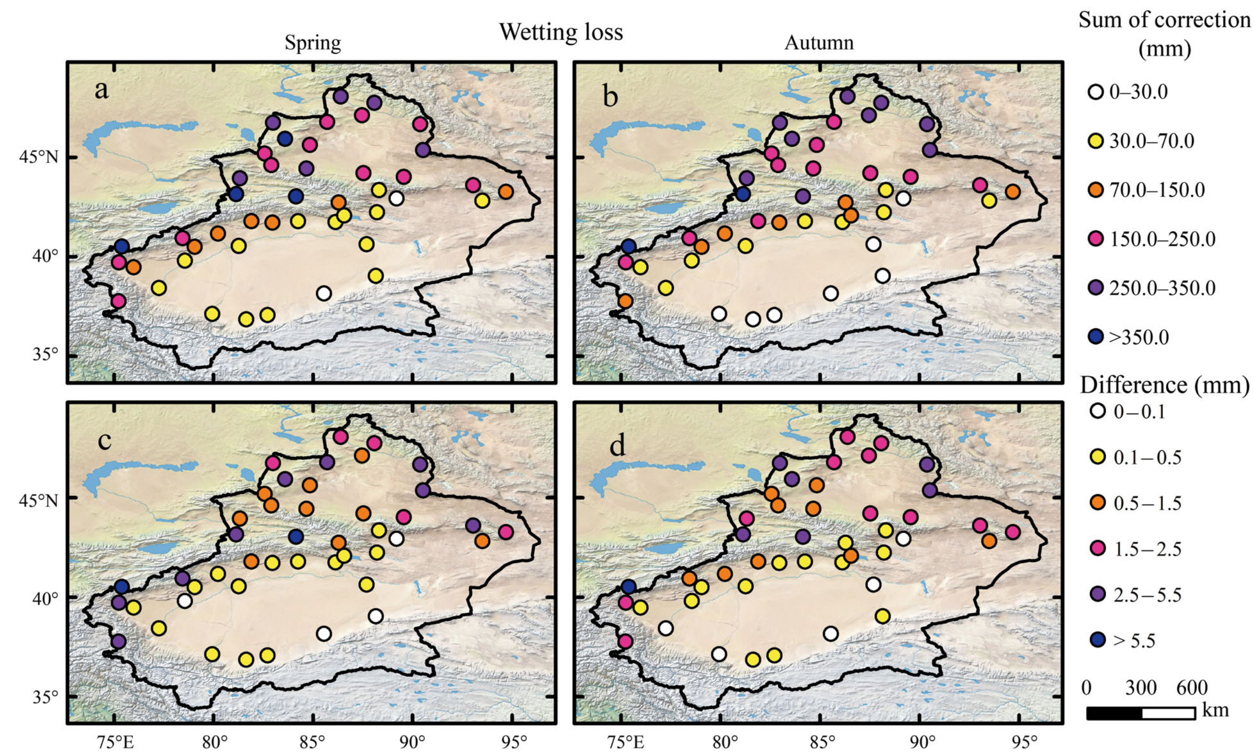

Fig. 4. (a,b) Sum of daily corrections for wetting loss and (c,d) the differences resulting from the 2 methods of dividing different precipitation days in spring and autumn in Xinjiang from 1960 to 2014. Method 1 is the new scheme proposed by Ding et al. (2014). Method 2 is the dual temperature threshold method (–2°C/2°C) (Zhang et al. 2004, Ye et al. 2007). The sum of wetting loss correction based on Method 1 at each station minus that based on Method 2 at each station equals the difference for wetting loss correction

ting loss. The sum values of corrections for wind-induced loss at most of the meteorological stations in North Xinjiang are higher than those in South Xinjiang in spring. The sum values on the south slope of the Tianshan Mountains are lower than those on the north slope in the 2 seasons. The sum values decrease from the south slope of the Tianshan Mountains to South Xinjiang in autumn. Generally, the sum values of corrections in autumn are slightly lower than those in spring. The sum values of corrections for wind-induced loss based on Method 1 are higher than those based on Method 2 in spring and autumn. In terms of differences, the sum values in North Xinjiang are greater than those in South Xinjiang in both seasons. The sum values of differences on the north slope of the Tianshan Mountains are higher than those on the south slope in spring and autumn.

Sum of daily total corrections (mm) for trace precipitation, wetting loss, and wind-induced loss (Fig. 6a,b) and the differences (Fig. 6c,d) resulting from the 2 methods of distinguishing different precipitation types in spring and autumn in Xinjiang from 1960 to 2014 are presented in Fig. 6. The sum of daily total correction for trace precipitation, wetting loss, and wind-induced loss based on Method 1 at each station minus that based on Method 2 at each station equals the difference for total correction. The sum values in spring and autumn are higher in North Xinjiang than those in South Xinjiang. The sum values of total corrections are larger on the north slope of the Tianshan Mountains and smaller on the south slope in the 2 seasons. The sum values of corrections decrease from the south slope of the Tianshan Mountains to South Xinjiang both in spring and autumn. As for as the differences, the sum values are larger on the north slope of the Tianshan Mountains and smaller on the south slope in the 2 seasons on the whole. A decreasing trend from the south slope of the Tianshan Mountains to South Xinjiang can be observed in spring and autumn.

4.3. Comparison of correction in North, Middle, and South Xinjiang

Sums of daily corrections (mm) for trace precipitation (Fig. 7a,b), wetting loss (Fig. 7c,d), wind-induced loss (Fig. 7e,f), and the total correction of the 3 losses (Fig. 7g,h) based on Method 1 of distinuishing different precipitation types in spring and autumn in the

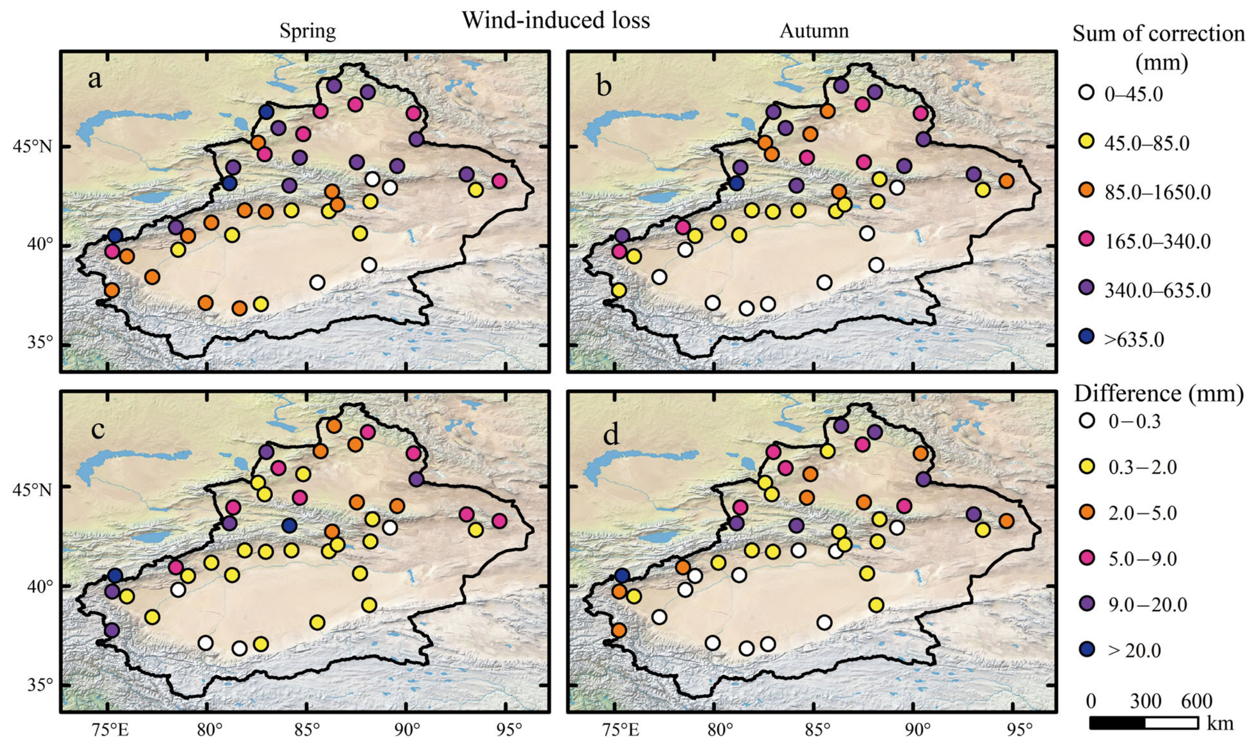

Fig. 5. (a,b) Sum of daily corrections for wind-induced loss and (c,d) the differences resulting from the 2 methods (see Fig. 4) of dividing different precipitation days in spring and autumn in Xinjiang from 1960 to 2014. The sum of daily wind-induced loss correction based on Method 1 at each station minus that based on Method 2 at each station equals the difference for wind-induced loss correction

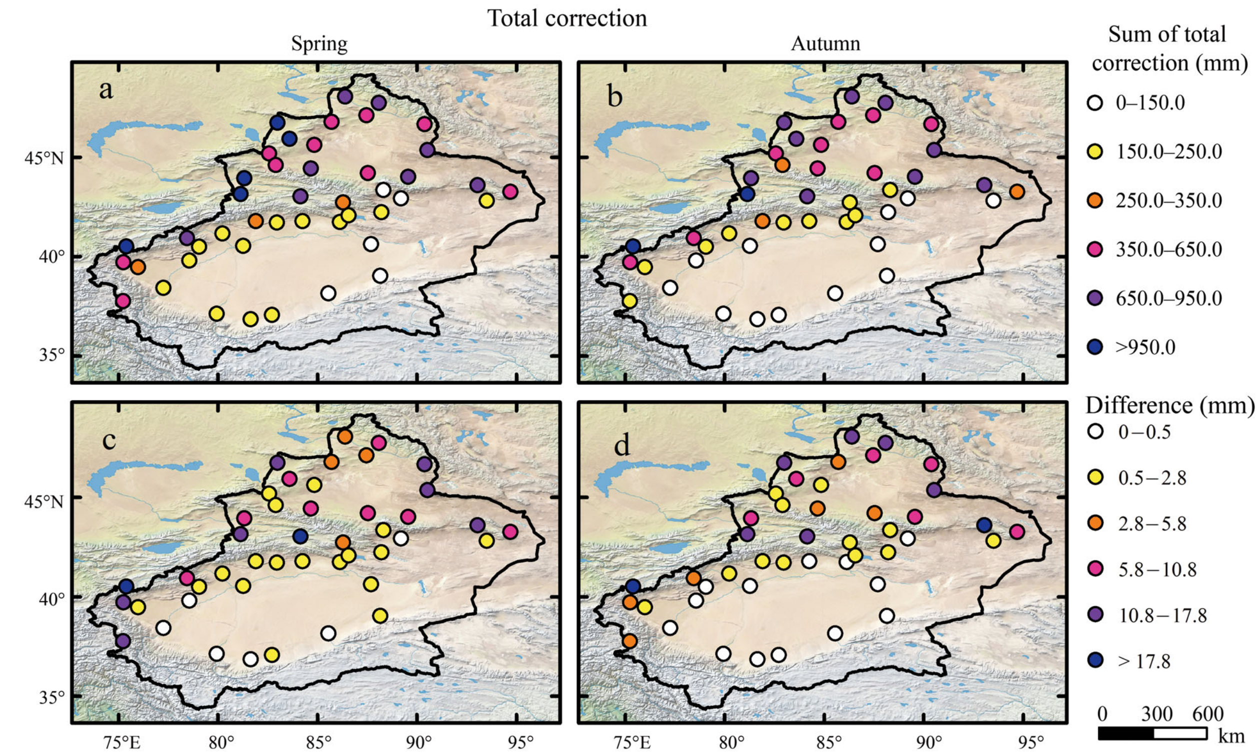

Fig. 6. (a,b) Sum of daily total corrections for trace precipitation, wetting loss and wind-induced loss and (c,d) the differences resulting from the 2 methods (see Fig. 4) of dividing different precipitation types in spring and autumn in Xinjiang from 1960 to 2014. The sum of daily total correction for trace precipitation, wetting loss and wind-induced loss based on Method 1 at each station minus that based on Method 2 at each station equals the difference for total correction

northern (north of 45.5° N), middle (between 42.5° N and 45.5° N), and southern regions (south of 42.5° N) of Xinjiang from 1960 to 2014 are compared in Fig. 7. The sum values of corrections for each loss demonstrate uniform characteristics in general in the 2 seasons. The median values in North Xinjiang are higher than those in the middle region of Xinjiang, which are higher than those in South Xinjiang. The median values of the sum of the total correction in North, Middle and South Xinjiang show similar characteristics compared to the sum of each correction. They are 623.01, 622.14, and 209.59 mm in spring, and 716.80, 478.29, and 157.48 mm in autumn in North, Middle and South Xinjiang, respectively.

4.4. Comparison of precipitation before and after correction

Fig. 8 exhibits a comparison of annual mean precipitation before and after the correction for trace precipitation, wetting loss, and wind-induced loss based on Method 1 of dividing different precipitation types at typical meteorological stations in the northern (Altay), middle (Bayanbulak), and southern regions (Yutian) of Xinjiang from 1 January 1960 to 31 December 2014. As shown, the total precipitation after correction increases to a certain degree compared to precipitation before correction at the 3 typical meteorological stations in Xinjiang. The correction at Bayanbulak in the Tianshan Mountains is larger than that at Altay in North Xinjiang, and the correction at Yutian in South Xinjiang is the smallest. The annual means of corrections for Bayanbulak, Altay, and Yutian are 81.48, 54.60, and 12.55 mm, respectively. The observation error correction can reflect the size of the error but not the relative correction of the precipitation. The correction factor (CF, %) is defined as the ratio of the correction to observed precipitation, which reflects the relative size of the correction (Ye et al. 2004). Given space limitation, the annual mean observed precipitation, annual mean total correction, annual mean precipitation after correction, and annual mean total correction factor at each meteorological station of Xinjiang from 1960 to 2014 based on Method 1 of distinguishing different

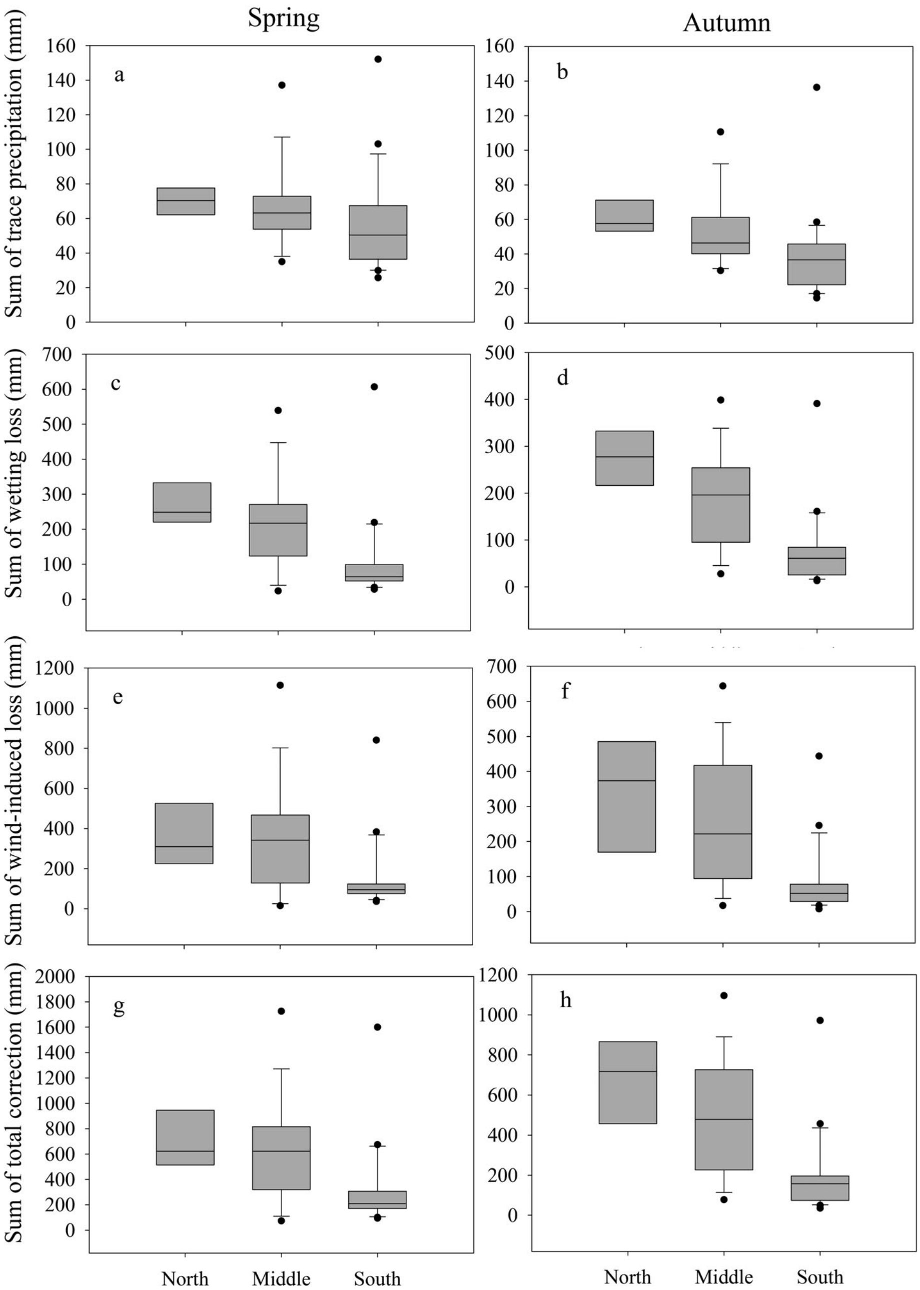

Fig. 7. Sum of daily corrections for (a,b) trace precipitation, (c,d) wetting loss and (e,f) wind-induced loss and (g,h) the total correction of the 3 losses in spring and autumn in the northern (north of 45.5° N), middle (between 42.5° N and 45.5° N) and southern region (south of 42.5° N) of Xinjiang from 1960 to 2014 based on Method 1 of dividing different precipitation types. Top and bottom of box: 75th and 25th percentiles; midline: 50th percentile (median); whiskers: 10th and 90th percentiles; dots: 5th and 95th percentiles

precipitation types are presented in detail in Table S3. The annual mean values of observed precipitation at all stations range from 15.03 to 503.54 mm. The annual mean values of total correction at all stations vary between 8.66 and 101.93 mm. The annual mean total correction factors at all stations in Xinjiang range from 13.55 % to 57.62 %.

5. DISCUSSION

5.1. Improvement in the correction method

The determination of precipitation type cannot be ignored during wetting loss correction and wind-induced loss correction. Accurate methods for distinguishing different precipitation types ensure the accuracy of the correction of precipitation observation errors. Traditionally, precipitation types are identified with air temperature-based methods (−2.0°C and 2.0°C) (Zhang et al. 2004, Ye et al. 2007). However, many studies indicate that the temperature ranges of different precipitation types have certain overlapping values, and the same precipitation type in different regions can correspond to different temperature ranges (Yang et al. 1998b, Fassnacht et al. 2001, Fassnacht 2004, He et al. 2009). Therefore, distinguishing different precipitation types according to the daily average temperature may create great uncertainty in precipitation correction studies, especially for Xinjiang with complex terrain and climate conditions (Yuan & Yang 1990, Zhang & Zhang 2006). As many recent articles focused on precipitation type determination, some improved methods can be applied to describe the precipitation observation error in Xinjiang.

The parameterized scheme used in this paper exhibits robust performance for determining precipitation types (Ding et al. 2014). The evaluative accuracy exceeded 86 % in Northwest China and other regions in China (Ding et al. 2014). The temporal stability of the new scheme was also investigated, and the accuracy was approximately 88 % (Ding et al. 2014). The

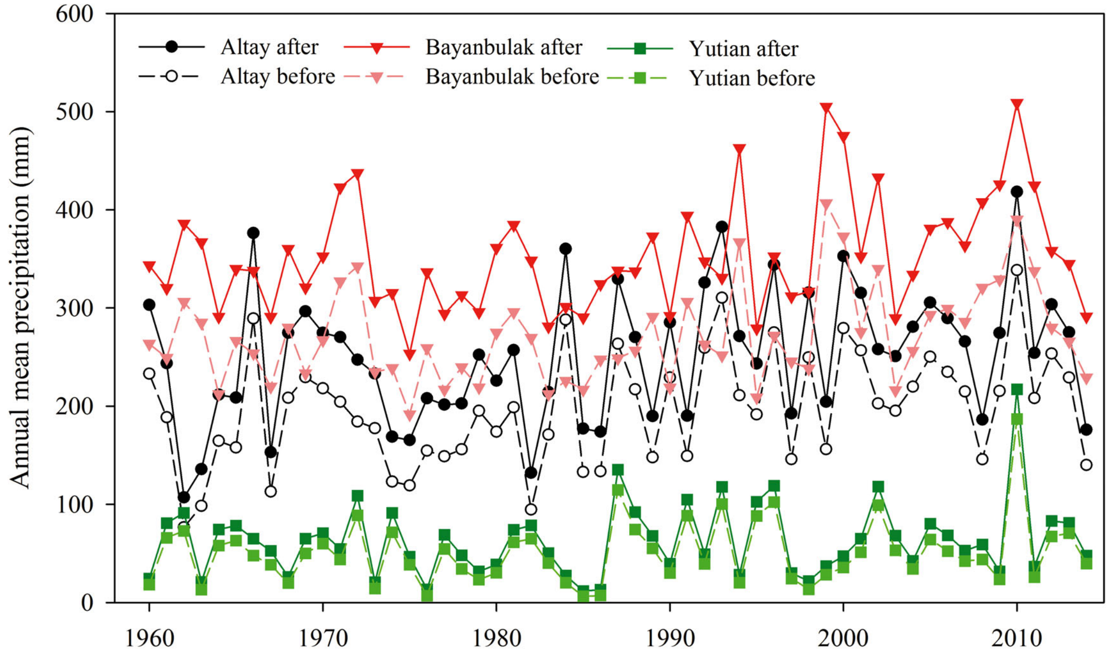

Fig. 8. Annual mean precipitation before and after the correction for trace precipitation, wetting loss and wind-induced loss based on Method 1 of dividing different precipitation types at typical meteorological stations in the northern (Altay; 47.73° N, 88.08° E), middle (Bayanbulak; 43.03° N, 84.150 °E) and southern region (Yutian; 36.85° N, 81.65° E) of Xinjiang from 1 January 1960 to 31 December 2014

accuracy is greatly improved compared to that of the single threshold method (Yang et al. 1997) or dual-threshold method (Loth et al. 1993, Wigmosta et al. 1994, Hock & Holmgren 2005, Wang et al. 2011). In this paper, the new scheme and the traditional dual temperature threshold method (–2.0°C and 2.0°C) are compared to quantify the days with different precipitation types. The improvement of the new scheme is quantified considering the correction of precipitation observation errors. The more accurate method of distinguishing precipitation types (rain, snow, and mixed) provides assurance of more precise precipitation correction.

5.2. Improvement in data pre-processing

The relocation of meteorological stations, and other factors causing data inhomogeneity, should be considered in climate studies. Checking data homogeneity before the data are used is recommended by many recent investigations, while this problem in data pre-processing was usually ignored in previous studies.

Over the past 20 yr, the rapid urbanization in China, including the oasis expansion in Xinjiang, has led many weather stations being relocated from urban (previously rural) to rural sites. In the 30 yr long-term climatology issued by China Meteorological Administration, the meteorological records are additionally marked as a new station when the horizontal relocation was >50 km or vertical relocation was >100 m. Accordingly, the daily data from 4 meteorological stations (Urumqi, Shisanjianfang, Hongliuhe, and Wenquan) were removed according to the metadata of meteorological stations in Xinjiang. Undoubtedly, strict data pre-processing has guaranteed improvement of the precipitation observation bias correction.

6. CONCLUSIONS

The daily precipitation data collected at 45 meteorological sites in Xinjiang over 55 yr (from 1 January 1960 to 31 December 2014) were corrected in terms of wetting loss, trace precipitation, and wind-induced loss based on 2 judgement methods of precipitation types in this study. We applied an error correction method to precipitation observations based on a series of experiments organized by the World Meteorological Organization in the Urumqi River Basin, China. The improvement in the correction of precipitation observation errors mainly resulted from an improved method for distinguishing precipitation types. The corrections of trace precipitation, wetting loss, and wind-induced loss show clear spatial distribution characteristics in spring and autumn. The differences of correction for each loss and total correction show similar spatial distribution characteristics in the 2 seasons. Additionally, corrections for each loss in North, Middle, and South Xinjiang from 1960 to 2014 are compared. On the whole, similar characteristics can be found; that is, the medians in the northern region are higher than those in the middle region, and the medians in the southern region of Xinjiang are the smallest relatively. Furthermore, the total precipitation after correction increased compared to that before correction.

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