RECONSTRUCTION OF HISTORICAL CLIMATE IN CHINA

High-Resolution Precipitation Data from Qing Dynasty Archives

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Chinese historical documents contain abundant descriptions of weather conditions that can be used to reconstruct the climate over hundreds and perhaps thousands of years—in this case precipitation between 1736 and 1911.

Long-term, high-resolution climate data are needed to study regional climate variability on decade-to-century time scales, and for evaluating climate model simulations of past climate. Historical documents, in which weather conditions are described qualitatively, and sometimes even quantitatively, provide a unique source for climate reconstruction of the past few centuries (Zhang and Crowley 1989; Bradley et al. 1993; Pfister 1995; Mikami 1999; Pfister et al. 2002; Ge et al. 2003).

In China, abundant historical documents, such as official histories, local gazettes, and "Memos-to-Emperor" exist, dating back hundreds and even thousands of years (Zhang and Gong 1980; Zhang 1982; Wang and Zhang 1988; Ge and Zhang 1990; Marks 1998). These documents have been used to reconstruct precipitation and temperature estimates (Chinese Meteorological Administration 1981; Zhang and Wang 1989, 1991; Wang et al. 1992; Zhou et al. 1994) for studying spatial and temporal patterns (Ronberg and Wang 1987; Zhang et al. 1994; Zheng et al. 2001; Zheng et al. 2005).

We report here on a concerted effort in China to use the Yu–Xue–Fen–Cun (雨雪分寸) records contained in Memos-to-Emperor during the Qing Dynasty (1644–1911), together with a field measurement program, to reconstruct high-resolution, quantitative precipitation data.

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"YU–XUE–FEN–CUN" RECORDS. During the Qing Dynasty, memos to the Emperor, reporting daily administrative activities, were sent regularly by designated provincial and local government officials around the country. The first memo that contained weather information, written in response to a specific request from the emperor, was prepared by Li Xu (who held the official position "Zhizao" in charge of textile products) in the thirty-second year (1693) of the Kangxi Reign. However, not until 1736, the first year of Emperor Qianlong, was daily information of "*Yu* (雨, rainfall)–*Xue* (雪, snowfall)–*Fen* (分, Chinese length unit, approximately 0.32 cm)–*Cun* (寸, 10 Fens)" regularly recorded, and the reporting continued until the third year (1911) of the Xuantong Reign. The records, covering 273 administrative sites within the 18 provinces and the special region of Shengjing (see Fig. 1), were included in the Memos-to-Emperor that were submitted concurrently but separately by both civilian and military officials, thus, providing a cross check of the accuracy and better continuity of the records.

Most of these memos are stored in the Chinese First Historical Archive in the Beijing Palace Museum, while a small number that were published are kept in the Taipei (Taiwan) Palace Museum. Many years of effort were spent by the Institute of Geography (now the Institute of Geographical Sciences and Natural Resources Research), Chinese Academy of Sciences, to extract the weather-related information that is intended for climate reconstruction. The effort has been part of the joint agreement, "Climate Sciences," between China's Ministry of Sciences and Technology and the U.S. Department of Energy (Riches et al. 2000).

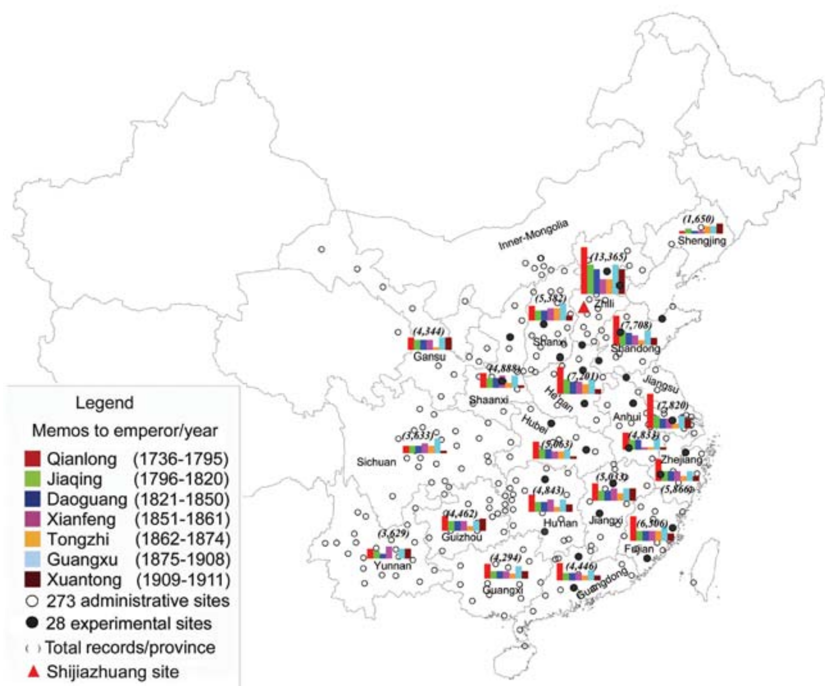

FIG. 1. The 273 administrative sites where Yu (rainfall)–Xue (snowfall)–Fen (Chinese length unit, approximately 0.32 cm)–Cun (10 Fens) records existed during the Qing Dynasty (1644–1911). Each record contains many observations within the administrative domain governed by the site administrator who was designated by the emperors to submit the memos in which the precipitation events were reported. Note that the reign of Qianlong has the most records, while the reign of Guangxu has the second most records. Field experiments were conducted at Shijiazhuang (red triangle) to facilitate the use of Yu–Xue–Fen–Cun for precipitation reconstruction. Similar experiments are planned at an additional 28 sites with different soil characteristics and climate conditions. Note that the six sites in Inner Mongolia were in the purview of Shanxi Province during the Qing Dynasty, and Zhili and Shengjing are, respectively, the present-day Hebei and Liaoning Provinces.

As indicated in Fig. 1, 104,966 records of Yu–Xue–Fen–Cun were extracted, each documenting the precipitation information of either the Yu–Fen–Cun (rain infiltration depth) or the Xue–Fen–Cun (snow depth). The former is the depth of the moisture penetration after the rainfall, determined by the wet–dry boundary identified by digging into the soil in "designated" flat farmland, and the latter is the snow depth on the surface after snowfall, taken at the same locations. Note that each record contains many observations within the administrative boundary governed by the site administrator who submitted the memos, and that the records were submitted only when precipitation events occurred. Other information that is contained in the records includes the date and duration of the precipitation events, as well as their implications for crop growth. The total number of records exhibits uneven temporal and spatial distribution, for example, 50,979 records during the Qianlong Reign (1736–95) and 19,293 records

Fig. 2. (a) An example of Yu–Fen–Cun (infiltration depth of rainfall into the ground) is dated 11 Jul 1743 (the 20th day of the fifth month in the eighth year of the Qianlong Reign in the Chinese lunar calendar). The 2 pages are the first and last page (right to left) of the original 12-page memo prepared by Gao Bin, Governor General of Zhili province (see Fig. 1). The thin handwritten words are Gregorian calendar converted from Chinese lunar calendar, while the red handwritten words on page 2 are the emperor's comments after reading the memo. The rainfall list was shown for each administration unit (Fu) of the Zhili province: 1) on page 1 (from right to left) "On the June 23 (2nd day of the fifth month in lunar calendar), Yongping Fu: Linyu county 3 cuns; On the June 24, Jizhou Fu: Xinhe county 3 cuns"; 2) on page 2, a comment by Emperor Qianlong: "I see, the capital Beijing was not in severe drought, but I still expect the rainfall." (b) An example of Xue–Fen–Cun (depth of snowfall) dated 6 Jan 1744 (the 22nd day of the 11th month on the eighth year of the Qianlong Reign in the Chinese lunar calendar). The two pages are the first and last page (right to left) of the original six-page memo prepared by Gao Bin, Governor General of Zhili Province (see Fig. 1). 1) On page 1, "On the Dec. 26 (11th day of the eleventh month in lundar calendar), Zhengding Fu: Gaocheng county 3 cuns; Jinzhou county 2 cuns; Wuji county 2 cuns; Pingshan county 2 cuns. Shunde Fu: Guangzong county 1.5 cuns; Tangshan county 1 cun"; 2) on page 2, a comment by Emperor Qianlong: "read it." (c) An example of qualitative description of rainfall. This 10 Jul 1772 rainfall memo was reported by Xu Ji, Governor General of Shandong province in the 10th day of the sixth month in Chinese lunar calendar on the 37th year of the Qianlong Reign (1772): "Some counties such as Licheng received rain in the middle of the fifth month, which was reported by me before. Recently, more than 50-counties of ten-Fus, such as Changqing county, had rain again with 2, 3, 4, to 5, 6 cuns and up to Shentou (enough depth into the soil from the 1st to 5th day on the sixth month in Lunar calendar (1-5/7). But in the nearby Licheng county of Ji'nan Fu, the rain is not enough, and the farmers were expecting rainfall. Now, in the 9th day of the sixth month (9/7), the rain started from HaiShi (Chinese ancient time, 9:00pm–11:00pm) to the next WuShi (11:00am–1:00pm) in Licheng county; it was in time and has penetrated into the arable soil"; 2) a comment by the emperor: "It's great to hear about this report."

during the Guangxu Reign (1875–1908), and more records for eastern China.

As shown in Fig. 2, each record of Yu–Xue–Fen–Cun contains information of either quantitative values or qualitative descriptions (and occasionally both) of the precipitation events. Although the quantitative values can be used directly, the qualitative descriptions require subjective interpretation. For example, description of the precipitation events includes many categories, such as *Rui Xue* (瑞雪, enough snowfall for crop growth), *Shen Tou* (深透, the rain infiltrated into the arable layer below), *Yu Xue You Zhan* (雨雪优沾, a little bit more rainfall or snowfall), and *Da Yu Lian Mian* (大雨连绵, continuous heavy rainfall). These records can be subjectively quantified according to their Chinese meaning. But for some precipitation events, both qualitative descriptions and quantitative values were specifically documented. For example, as shown in Fig. 2c, Shen Tou was used as the next category right after 6 cuns, so this description was assigned as 7 cuns, and, for Zhili province (the present-day combined area of Hebei province, Beijing, and Tianjin), there were 17 (out of 22) records in which Shen Tou was referred as 7 cuns. *Ji Qi Shen Tou* (极其深透) and *Ji Wei Tou Zu* (极为透足) (too much rainfall) were subsequently assigned 8 cuns, although the depth could be larger than 8 cuns but is definitely smaller than 10 cuns, because that was explicitly recorded. Moreover, there also exist some descriptions, such as *Yu Shui Tiao Yun* (雨水调匀, normal rainfall), *Yu Yang Shi Ruo* (雨旸时若, normal rainfall and sunshine), *Yu Shui Guo duo* (雨水过多, too much rainfall), and *Wang Ze Shen Yin* (望泽甚殷, urgent need of rainfall), to assess the precipitation amount during a short time (e.g., a month or season). Although these descriptions cannot be quantified directly, they do provide evidence with which to cross check the quantitative values. The system is subjective, but it does reflect degrees of consistency in precipitation amounts. Table 1 summarizes the descriptive measures of precipitation events and the corresponding assigned quantitative values used in the precipitation reconstruction.

It is worth noting that the administrative reporting system at that time was unique, which increased the confidence in the accuracy and continuity of the Yu–Xue–Fen–Cun.

- The report was confidential and could only be prepared by the reporting officials personally.
- There were several sources for reporting the same event and the emperor paid particular attention to Yu–Xue–Fen–Cun because of its significance for crops and crop yields. For example, Aertai, Governor General of Shandong Province, reported "Every county in Taian Fu received rain infiltrating into the arable layer below (Shen Tou in Chinese) on the 23rd, the fourth month

Table 1. The descriptive measures of precipitation and their quantitative equivalents.

Precipitation types	The descriptive measures of precipitation	Quantitative equivalents*
Rain	*Da Yu Lian Mian* (大雨连绵): Heavy rainstorm, continuous heavy rainfall for more than one day	12
	Da Pei Gan Lin (大沛甘霖): Heavy rain in one day	10
	Ji Qi Shen Tou (极其深透) and *Ji Wei Tou Zu* (极为透足): Too much rainfall for one day	8
	Shen Tou (深透): Much rainfall for one day, the rain infiltrated into the arable layer below	7
	You Zhan (优沾): A little bit more rainfall	6
	Zhan Zu (沾足): Normal rainfall	5
	Wei Tou Zu (未透足): A little bit less rainfall	4
	Qian Zhan Zu (欠沾足): Not enough rainfall	3
	De Yu (得雨): Showers	2
	Bo Zhan (薄沾): Light showers	1
	Wei Yu (微雨): Occasional showers and the rain is less than 1 cun	0.5
Snow	*Ying Chi* (盈尺): Snowstorm, snow depth up to 1 chi	10
	Da Xue (大雪): Heavy snow	6
	Rui Xue (瑞雪): Enough snowfall for crops growth	4
	De Xue (得雪): Snow showers	2
	Xiao Xue Bo Zhan (小雪薄沾): Light snow	1
	Wei Xue (微雪): Flurries, and the snow is less than 1 cun	0.5

*Unit in Chinese cun, which is approximately 3.2 cm.

in lunar calendar of the twenty-seventh year of Qianlong Emperor (May 16, 1762); other Fu's received the rainfall around the end of the fourth month (14-23/5), and the soil is very wet." The emperor wrote that "your description is suspicious. The rain infiltration depth is less than 1 cun in Taian reported by Wang Jiongfu, then why was it described as Shen Tou?"

- Local officials directly verified the quantitative data. For example, "Reported by Li Kentang, Governor General of Zhili province, in the fifty-seventh year of Qianlong Emperor (1792): There was little rain after the end of the third month (lunar calendar) in Tianjin, and the farmers were praying for rainfall. On the 25th, the fourth month in lunar calendar (15/5), it was raining heavily. I went to farmland to dig into the ground by myself, and the depth of infiltration has reached 4 cuns."

Like most historical documents, the records of Yu–Xue–Fen–Cun have gaps, resulting from damage due to poor archiving, fire, theft, and other factors. In particular, most missing reports were concentrated in 1751–52, 1787–89, 1801, 1837–39, 1845, 1852, 1860, 1864, and 1870–71, which accounted for 8.6% of all of the data. In addition, for reasons given below, it is highly unlikely that there were precipitation events that were not reported. First, the memo was the most efficient reporting system in the Qing Dynasty. A special office was set up outside the Qianqing Gate of the Forbidden City every morning between three and four o'clock to receive the memos that were delivered by special messengers from the provinces, which were then delivered to the emperors. Second, it was the responsibility of local officials to routinely record each rainfall/snowfall event, and severe punishment resulted if mistakes were caught. But, most important of all, the emperors installed four independent observing and reporting systems—an administrative branch, a military officer, an education officer, and traveling high-ranking officials who were sent out either publicly or privately by the emperor for special investigations. The information from these different channels can, therefore, provide a cross check of the report accuracy, and also can verify whether there were any missing precipitation events.

PRECIPITATION RECONSTRUCTION AT SHIJIAZHUANG.

To convert the Yu–Fen–Cun (soil penetration depth) into quantitative rainfall amount requires establishing the relation between the two, which depends on the soil characteristics (capacity to hold water, runoff, etc.), its initial moisture content, and rainfall duration and intensity. To establish the correlation, a field experiment was conducted following the same measurement method documented in the historical records.

Field experiments. The experiment was conducted at the Luancheng Agricultural Ecosystem Experimental Station, an ecological site operated by the Chinese Academy of Sciences (Fig. 3; Zheng et al. 2004) in Shijiazhuang (located at red triangle in Fig. 1). An artificial rainfall device was used for the experiments on the farmland during the period of 30 May–16 June 2002, the wheat-growing season. Because the infiltration depth is sensitive to rain intensity and total amount, a combination of different rain intensities (0.21, 0.42, 0.83, 1.25, and 1.67 mm min^{-1}) and total amounts (6.25, 12.5, 25, 37.5, 60, 75, 85, and 100 mm) was used to provide the categories of light rain (0.1–10 mm), moderate rain (10–25 mm), heavy rain (25–50 mm), and rainstorm (50–100 mm). The initial soil moisture content, measured before starting the rainfall, had values from 4.6% to 15.0% (corresponding to 24.2%–78.8% of the soil field capacity). The range represents soil moisture characteristics from very dry to wet. The depth of infiltration was measured after rainfall. The measurement included 14 sets of rainfall conditions, and, for each set, three identical experiments were repeated to assure the significance of the results. The valid data sample of 41 (one sample was invalid due to an instrumental problem) was used to obtain an empirical relation between rainfall (P_r, mm) and the infiltration depth (Z_f, mm), $P_r = 1.6882 \times 10^{-4} Z_f^2 + 0.1298 Z_f$. This relation explains 87% of the precipitation variance with statistical significance at the 0.1% level.

During the measurement period, there was only one natural rainfall event. On 9 June 2002 the rain started in the morning and continued throughout the day, yielding a total amount of 25 mm. The rain infiltration depth and soil moisture content were measured the next morning in the field where the artificial rainfall experiments were conducted, and the rainfall penetration depth was

FIG. 3. Instrumentation at the field experiment conducted at Luancheng Agricultural Ecosystem Experimental Station (37.8°N, 114.7°E) in Luancheng County, Hebei Province.

found to be 16 mm. From the empirical relation, the measured infiltration depth of 16 mm yielded a total rainfall amount 25.09 mm, which is very close to the measured 25 mm, thus providing a validity check of the empirical relation.

It should be noted that during the rainy season, the reconstructed precipitation should be adjusted further by an infiltration coefficient—a factor accounting for the runoff that was not considered in the artificial rainfall experiments. The factor is particularly important during the rainy season (from June to September). According to a study by Ren et a1. (1985), the coefficient of most sandy loam areas in the rainy season is 1.00, 0.84, 0.72, and 0.46 for light, moderate, heavy, and rainstorm events, respective1y. For Shijiazhuang, we used the daily precipitation data from June to September during the period 1981–2000 to establish the relationship between the precipitation amount and the different categories of rain intensity. They were subsequently used to calculate the infiltration coefficient.

The record of Xue–Fen–Cun corresponds to snow depth in modern meteorological data, so we can convert these records into precipitation amounts that are directly based on the relationship between the two parameters from the instrument measurements. In the daily observations, both the precipitation and snow depth are available. But, the depth is snow accumulation on the ground, not accumulation for each individual event. Therefore, we have to restrict the selection of the data to the cases in which no snow accumulation occurred before this particular snowfall. Twenty-two cases were identified from observational data at Shijiazhuang in January during 1951–2000, and they were used to derive the empirical equation, $P_s = 0.0757H_s$, where P_s is snowfall (mm) and H_s is snow depth (Xue–Fen–Cun, cm).

Precipitation reconstruction. Given the empirical relations for both the rainfall and snowfall, the reconstruction procedure was conducted as follows. First, the quantitative records of Yu–Fen–Cun and Xue–Fen–Cun were extracted from the documents, while the qualitative descriptions were converted into quantitative values using the categories, defined according to their Chinese meaning, and numerical values, defined when both quantitative and qualitative information coexisted, as summarized in Table 1. Second, the precipitation for each record was calculated using the two empirical relations described above. Following this, the precipitation estimates were added by month to yield monthly precipitation series over the period 1736–1911. Finally, the seasonal time series was calculated from monthly data.

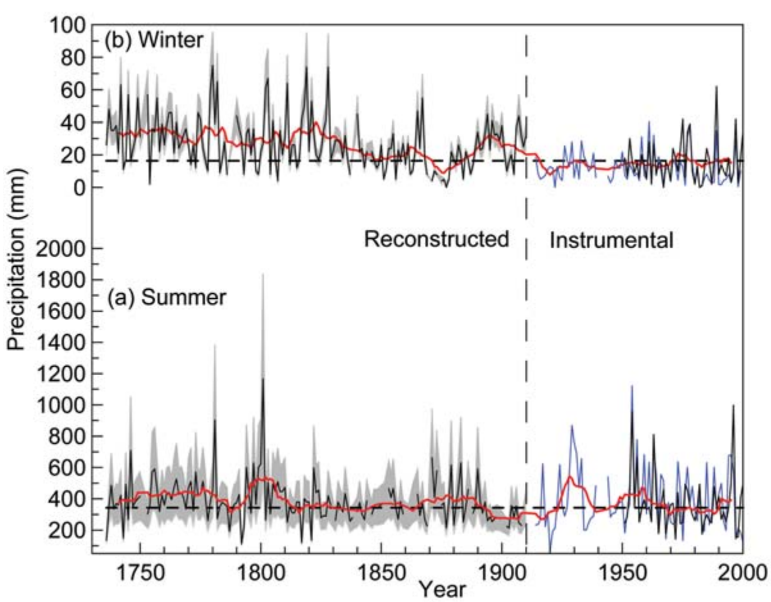

Fig. 4. Reconstructed 1736–1911 and instrument-measured 1951–2000 summer and winter precipitation (mm, black line) at Shijiazhuang. The red line represents 11-yr running mean values, while the horizontal dashed line is the mean annual value of 1961–90. The shading represents the 95% confidence boundary. Because of the missing 1911–50 measurements at Shijiazhuang, the seasonal instrumental precipitation measurements at the neighboring city, Baoding (the blue line; located 125 km northeast of Shijiazhuang), are used for comparison. Note that the 11-yr running mean values from 1911 to 1950 are based on the precipitation measurements at Baoding.

The precipitation reconstruction for Shijiazhuang is shown in Fig. 4. It can be seen that the summer and winter precipitation derived from the historical records were generally greater than the 1961–90 means, with much larger fluctuations in summer. Note that the characteristics of a wetter climate during the Little Ice Age were also demonstrated in the climate model simulations by Liu et al. (2004). During the winter, there existed a decreasing precipitation trend for the period 1825–75 and an increase afterward, reaching the pre-1825 level. Shijiazhuang, influenced by the East Asian summer monsoon, showed significantly large fluctuations in the summer precipitation, with a distinctive wet period from 1785 to 1815 separating a relatively wetter earlier period and a latter period, with precipitation closer to the 1961–90 means. The instrumental data show a decreasing trend in summer precipitation starting in 1951, although it became wetter in the 1990s.

It is worthwhile to comment on two extreme events identified in Fig. 4—a 1792 drought with a total rainfall estimate of 112 mm, and an 1801 flood of 1167 mm. The drought case has been explicitly cited in several other historical documents. For example, the Imperial Edicts of Emperor Qianlong in Zhili Province read 1) "in the south of Beijing (Shijiazhuang located at the south of Beijing), all Fu's and Zhou's did not have enough rain, the drought status were already established, written on July 28, 1792"; 2) "in the south of Beijing, the winter wheat was lean, and most of area was drought, recorded on Aug. 16, 1792"; 3) "the Imperial Edicts recorded on September 4, 1794, this year (1794), some places, e.g. Zhengding Fu, were flooded, but the disaster was lighter than 1792, at that year, the crops were almost no harvest, and the farmers were hungry." Zhang (1995) further reported the severity of the drought event, "Zhili province was in severe drought, the emperor had to permit farmers to enter into northeast of China, in order to make a living."

According to the description in the Memos-to-Emperor, the 1801 heavy rainfall event started in 28 June, covering the whole of the Zhili Province. The main rainfall occurred during the period 10–17 July, while intermittent rainfall lasted until early August. This rainfall event had the characteristics of heavy precipitation with long duration, as reported by 1) Jiang Sheng, Governor General in Zhili province in Yu–Xue–Fen–Cun, "120 counties in Zhengding (today Shijiazhuang), Tianjin, Hejian Fu et al., received rain with 3-cuns, 4-cuns, 5-cuns and Shentou on June 27–29, and Beijing and the south has received the timely rain simultaneously"; 2) an official from Shengzhu "From Shenshi (15:00–17:00, Chinese ancient time) of July 10, the rain was heavy and continuous from day-to-night everywhere, until it stopped July 17, after July 18, the rain and sunshine occurred alternately"; and 3) in the Imperial Edicts "Zhili province was in flood, and victims of a natural calamity were very hungry . . . now, an emergency funding has been released to relieve these people near Beijing, but as far as how to take actions in other counties, should be report to me as soon as possible."

Note that the year 1801 total estimated precipitation of 1167 mm is larger than the recently observed summer total of 998 mm in 1996. The 1801 heavy precipitation event might have been associated with an abnormal large-scale circulation. To gain some insights hereon, we examined the circulation patterns associated with the largest heavy precipitation events in 1954, 1963, and 1996 in which the observed atmospheric circulation was available. When compared with climatology, the circulation in these 3 yr showed that the western Pacific subtropical high was further north and that the midlatitude westerly prevailed (Zhao 1999). However, there are differences in temporal variations of precipitation among the 3 yr. The heavy precipitation in 1963 was caused by the extreme cold burst during 4–9 August, which produced 736 mm (91% of the total summer precipitation) with a maximum 200.2 mm on 5 August. In 1996, the precipitation total of 555.8 mm (56% of total summer precipitation) was concentrated during 30 July–5 August, with a maximum of 359.3 mm on 4 August. However, the precipitation event in 1954 had a much longer duration, and when compared with the 1961–90 mean values, it rained 175 mm (254% above normal) in June, 488 mm (256% above normal) in July, and 295 mm (90% above normal) in August. The maximum daily rainfall was usually smaller than 100 mm. The records in 1801 indicate that it was closer to the behavior of the 1996 event, with an extreme cold burst during 10–17 July from which a total rainfall of 484 mm (42.3% of the total summer precipitation) resulted.

OUTLOOK. The combination of the historical records of Yu–Xue–Fen–Cun and modern field measurements, as shown here for Shijiazhuang, demonstrates the potential of reconstructing a high-resolution precipitation dataset dating back to the early eighteenth century. To follow up on this, an expanded field measurement program is planned for 28 more sites (see Fig. 1), in addition to Shijiazhuang. This program, taking into consideration different soil types and climate zones, will allow for the reconstruction of precipitation for 273 administrative sites where Yu–Xue–Fen–Cun records are available. In 2004, the field experiments were conducted, together with the compilation of Yu–Xue–Fen–Cun records. By the end of 2005, the empirical relation between penetration depth and rainfall for different soil types in different climate zones will be established based on 2 yr of experimental data. It is planned that by 2006, seasonal precipitation series at 273 sites will be reconstructed and preliminary analyses will be conducted.

One final note here: the Yu–Xue–Fen–Cun contains additional weather-related statistics, such as the number of rain days and associated precipitation intensity, which are also valuable in studying their long-term variability and to calibrate against other datasets, such as the Qing–Yu–Lu, in which the rain days dated back to 1724 are available for Beijing (see Wang et al. 1992, 1993).

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