



Extreme temperature of the mid-eighteenth century as compared to today's in Beijing

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Abstract

The extreme temperature events of the mid-eighteenth century can help understand the background climate conditions of the pre-industrial revolution period. However, studies are lacking mainly due to the scarceness of instrumental observations. Based on the observations made by the French Missionary Amiot in Beijing, a daily maximum and minimum temperature dataset during 1757–1762 was established using relationships developed with reference to modern observations of nearby stations. The first result of a comparison between the extreme temperature change of the mid-eighteenth century and the present situation (2014–2019) in central Beijing city shows: (1) There were mean annual summer days (the number of days with daily maximum temperature > 25 °C) exceeding 130 d, and tropical nights (the number of days with daily minimum temperature > 20 °C) of more than 52 d, as compared to more than 150 d and 80 d respectively at present; (2) The mean annual frost days (daily minimum temperature < 0 °C) and ice days (daily maximum temperature < 0 °C) were 126 d and 31 d, respectively, in 1757–1762, but only 110 d and 10 d, respectively, during 2014–2019; (3) The mean annual warm days (days when maximum temperature > 90th percentile) and warm nights (days when minimum temperature > 90th percentile) were 63 d and 30 d, respectively, compared to the present values of more than 65 d and 55 d, respectively; (4) The annual mean cool days (days when maximum temperature < 10th percentile) and cold nights (days when minimum temperature < 10th percentile) were approximately 52 d and 48 d, respectively, in 1757–1762, but they are fewer than 40 d and 30 d, respectively, today. Therefore, the occurrences of most warm events in the mid-eighteenth century were slightly lower than modern times, and the occurrences of most cold events were more frequent compared with those in modern times, with the decrease of cold events from 260 years ago to today more obvious than the increase of warm events. The rapid warming in Beijing in recent decades, especially in the urban center, has exerted a great influence on the change in

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extreme temperature indices, which may have been caused by both urbanization and global/regional warming.

Keywords Extreme temperature events · Mid-eighteenth century · Pre-industrial revolution · Climate change · Beijing

1 Introduction

The significant impacts of extreme temperature on human health and lives, societal infrastructure, agricultural production, species extinctions, energy consumption, and water resources management have been reported widely (e.g., Karl and Easterling 1999; Easterling et al. 2000; IPCC 2011). In recent years, the temporal and spatial characteristics of extreme temperatures and their changes have attracted a large amount of attention (e.g., Zhai and Pan 2003; Domonkos et al. 2003; Alexander et al. 2012; Vincent and Mekis 2006). Most studies have found that the occurrence of extreme temperature events has been reflected in significant changes in global land and regional mean temperature patterns worldwide in the past few decades, with the spatially consistent trends of warm events significantly increasing and cold events significantly decreasing (e.g., Sillmann et al. 2013; Liu et al. 2006; You et al. 2008; Zhou and Ren 2011; Yan and Liu 2014; Rahimzadeh et al. 2009; Manton et al. 2001; Panday et al. 2014; Sun et al. 2017a, b). The changes in extreme temperature are highly consistent with the observed global and regional climate warming in terms of annual mean surface temperature change.

It is obvious, however, that previous analyses were mostly focused on the past 50 or 60 years due to the lack of observations for other time periods. Extreme temperature change studies for earlier (pre-1950s) periods were limited to small-scale regions, including those reported for Italy, French, Norway, England, Australia, and Japan et al. (Cocheo and Camuffo 2002; Yan et al. 2002; Camuffo et al. 2010; Comes 2008, 2010; Jones 2001; Ansell et al. 2006; Hestmark and Nordli 2016; Zaiki et al. 2006; Können et al. 2003; Ashcroft et al. 2014; Lucas et al. 2019). There were also a few investigations that examined the 100-year extreme temperature change at a few cities in China (e.g., Yan et al. 2001a, b; Cui et al. 2009; Guo et al. 2011; Yu et al. 2020; Xue et al. this special issue). All of these studies are valuable for a robust detection and attribution of longer than five-decade extreme climate change in the local areas. Up to now, no work comparing the extreme temperature change of nineteenth century or even eighteenth century with those reported for the past few decades in China or the East Asian region has been reported, primarily because of the insufficiency of the early period temperature data. The surface air temperature data are particularly less available for the years before 1900 (Williamson et al. 2018; Bronnimann et al. 2019; Sun et al. 2017a). This situation is hindering our understanding of the early period extreme temperature change that could be taken as a background or benchmark of any changes of modern extreme climate.

Here we used the observations made by the French Missionary Joseph Amiot in Beijing, from 1757 to 1762, which may have been the earliest daily instrumental data with continuous records longer than 5 years in the East Asian region (Ren et al. submitted for publication). After digitation, quality-control and temporal interpolation, a continuous daily maximum temperature (T-max) and minimum temperature (T-min) dataset during 1757–1762 in Beijing was established based on the observations. The dataset would be highly valuable for understanding the background extreme climate status and variability in Beijing as well as in North China.

The next section describes the records of Missionary Joseph Amiot, and the process of establishing a daily T-max and T-min dataset with modern records from nearby stations as reference. This is followed in Section 3, by a description of the early-year extreme temperature events. The preliminary analysis of extreme events difference between 1757 and 1762 and modern times is briefly described in Section 4. Finally, a summary and prospective is given in Section 5.

2 Data and method

2.1 Data

Surface air temperature was observed and recorded by the French Missionary Amiot at a site in today’s Beijing Center during 1757–1762. The observation site was in the Old North Church (Lao Bei Tang) where Missionary Amiot preached, which is now located at Canchikou on the west bank of the Zhonghai Lake, less than 1 km to the west of the Forbidden City (Fig. 1).

The observational records included the surface air temperature, air pressure, and wind-direction twice a day and daily meteorological phenomena from January 1757 to December 1762. Ren et al. (submitted for publication) reported in detail the process of verification of instrument emplacement and observational time, the conversion of climatic variables to modern units, and the quality control of the data. The temperature was converted from

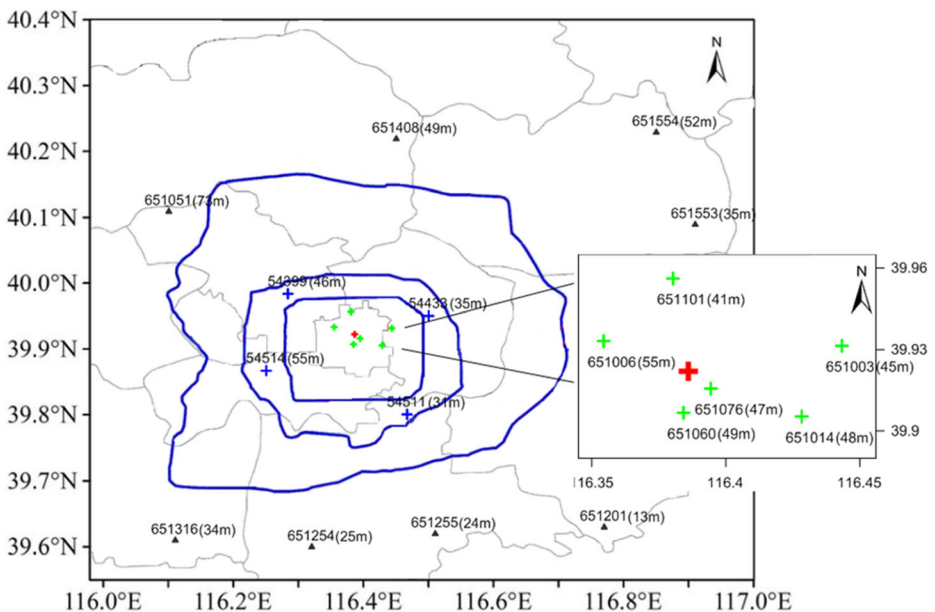


Fig. 1 The distribution of early observations (Old North Church) and the nearby national meteorological stations in Beijing (Red cross shows the location of Old North Church; Green cross shows the six nearest modern automatic meteorological stations (with observations of more than 10 years); Blue cross shows the four nearest modern national stations (with observations of more than 50 years) in different directions; Black triangle shows the eight rural automatic meteorological stations (with observations of more than 10 years); The numbers in brackets are altitudes of the stations in meter. The three hoops from inside to outside are the 4th Ring Road, 5th Ring Road, and 6th Ring Road, with the 4th Ring Road representing the central urban area of Beijing City

Reaumur Equals to Celsius ($^{\circ}\text{C}$) by multiplying by 1.25, and the observational time at the church was determined to be at 8:00 Beijing Time (BJT) and 15:00 BJT corresponding to the local time of the modern period.

We made an investigation of the instrument installation and the micro-environment of the observation, and were able to affirm that the thermometer was installed in a ventilated garret of the church, which was named as the Observatory. The comparison of mean seasonal and diurnal variations of air temperature with the modern observations of the nearby autonomous weather stations in the central area of Beijing City indicates that the thermometers were placed properly, and the ventilation was good. At that time, the main source of heat was due to cooking and heating in the main building of a church was unusual (Camuffo 2002). The Observatory and the kitchen were in two buildings of the Old North Church. The well-ventilated garret could help Missionary Amiot obtain observations similar to the outdoor ones (Cocheo and Camuffo 2000, 2002). However, there were several factors that could bring some uncertainties, for example, the accuracy of the equipment, the standard of observations at that time, the change of micro-environment around the church, and so on. These problems also sometimes trouble the modern observations worldwide. Overall, the air temperature records can thus be used with certain caution to make a comparison with those made at present.

The monthly number of records is shown in Fig. 2. In most months, the ratio of valid data for the two observational times exceeded 90%. Except for January 1757 and August to November 1758, all of the ratios of monthly valid data exceed 80%. Therefore, the completeness of the data in the 6 years is relatively good for a climatological analysis and a comparison with modern times. There was no interpolation made on the blank time.

2.2 The reconstruction of daily T-max and T-min

To help understand the extreme temperature events in mid-eighteenth century Beijing, and the difference of extreme temperature indices from those occurring in modern times, an interpolated daily T-max and T-min is needed. We assumed the relationship between hourly temperatures and the daily T-max and T-min during 1757–1762 were consistent with in

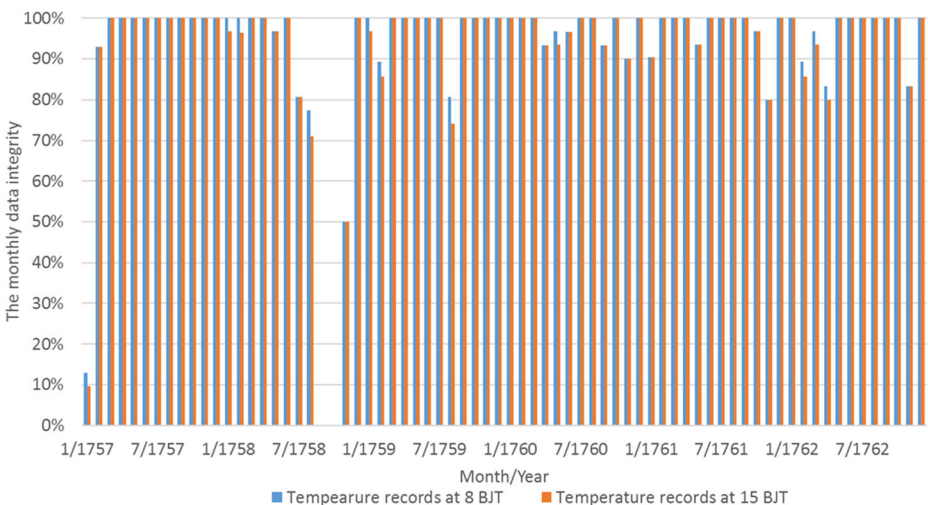


Fig. 2 The monthly ratio of the valid air temperature records at the Old North Church, Beijing

modern times. Based on the statistic relationship of the modern diurnal variation of temperature in the nearby locations, the daily T-max and T-min during 1757–1762 could then be reconstructed.

To develop regression formula, the observations of modern stations near Old North Church were applied. There are several automatic metrological stations (AWS) located near the ancient church, among which there were six located within 5 km from the early observational site (Fig. 1). The closest stations was 651,076 (Forbidden City), 1010 m away from the Old North Church; the other five stations were 651,060 (Nanchangan Street, 1710 m), 651,006 (Guanyuan, 2960 m), 651,101 (Rending Lake, 3820 m), 651,014 (Ancient Observatory, 4060 m), and 651,003 (Workers' Stadium, 4990 m), respectively. All of the stations were AWSs, which began observations in recent years and had a relatively poor data integrity for some periods. Therefore, the nearby national stations were also selected. These stations all had a record of more than 50 years, and kept continuous recordings throughout the observational periods. The closest national station was 54,433 (Caoyang), 10 km away from the Old North Church; the three others were 54,399 (Haidian, 11 km), 54,514 (Fengtai, 13 km), and 54,511 (Beijing, 15 km). The available hourly records of all four national stations started at 2000. The national stations were located farther from the Old North Church but had relatively longer hourly records, and the AWSs were located closer but the hourly data were available only for recent years, though they all had started observation in 2010.

Taking the distance and direction, the micro-climate and environmental similarity, and the length of records into consideration, the nearest modern national stations in the four quadrants around the Old North Church were chosen as reference stations to reconstruct the daily T-max and T-min during 1757–1762. The six nearby AWSs within 5 km were also selected to indicate the present climate of the 1757–1762 observational site. After 250 years, the surrounding of the Old North Church changed remarkably. To analyze the effect of the local observational environment change or urbanization, eight AWSs (Yang et al. 2013) in the suburban areas of Beijing City were also employed to represent the local observational environment similar to that of the Old North Church 250 years ago. The location of these rural stations is also shown in Fig. 1.

The comparison of the 6-year averaged hourly mean temperature for the 1757–1762 observations and the four nearby modern stations is shown in Fig. 3. The UTC 0 (Fig. 3a) and UTC 7 (Fig. 3b) hourly mean temperatures were compared, respectively.

The hourly mean temperature at UTC 0 in 1757–1762 was slightly lower than that in 2014–2019, but very similar with that in 1961–1967. An interesting phenomena was that the temperature difference between 1961 and 1967 and 1757–1762 was smaller than that between 1961 and 1967 and 2014–2019. The mean temperature difference was 1.1 °C between 1757 and 1762 Old North Church and 1961–1967 national stations, 4.1 °C between 1757 and 1762 Old North Church and 2014–2019 nearby AWSs. The mean temperature difference of the national stations between 1961 and 1967 and 2014–2019 was 2.2 °C, and the difference between 1961 and 1967 national stations and 2014–2019 AWSs was 3.0 °C. Due to the lack of observation at UTC 7 in 1961–1967, the hourly mean temperatures at UTC 7 in 1757–1762 were only compared with temperature in 2014–2019. The UTC 7 temperature in 1757–1762 in summer and early autumn were very close to that in the present time. The UTC 7 hourly mean temperature of the Old North Church during May–September was 29.8 °C, 0.26 °C lower than that of the nearby AWSs and 0.27 °C higher than that of the national stations.

Due to rapid urbanization, the city center has experienced a remarkable change since the pre-revolution era. The hourly mean temperature difference of the AWSs between urban center and rural areas was 1.9 °C for UTC 0 and 0.4 °C for UTC 7. The temperature differences were

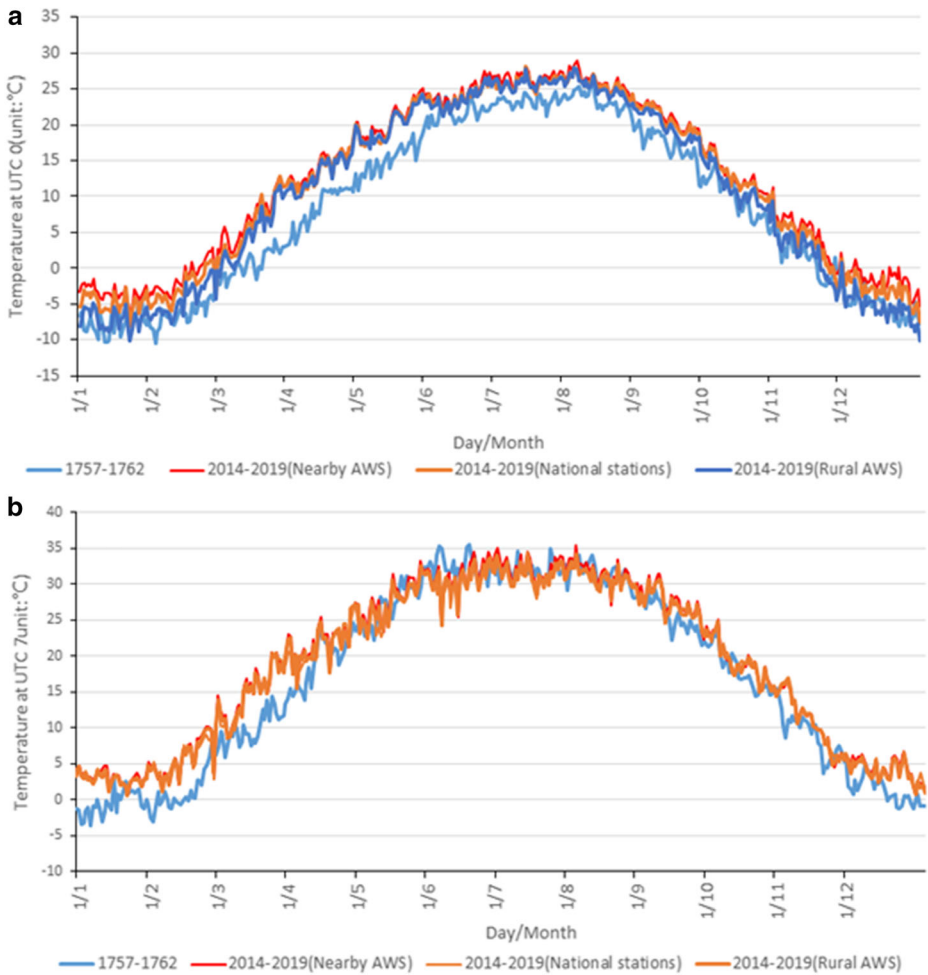


Fig. 3 Comparison of mean temperature at UTC 0 (a) and UTC 7 (b) for the different 6-year periods of 1757–1762, 1961–1967, and 2014–2019

equivalent to the urban heat island (UHI) intensity, which agrees with, but is slightly less than, those of central urban areas reported in Yang et al. (2013) that showed an average of 2.37 °C UHI intensity for the whole central urban area for 21:00–6:00 LST/BJT. The hourly mean temperature difference of 4.1 °C at UTC 0 between 1757 and 1762 Old North Church and 2014–2019 nearby AWSs should be caused jointly by global and regional warming, and the urbanization or the enhanced UHI intensity. It was thus possible that the global and regional warming might have induced an at most 2.2 °C hourly mean temperature increase at UTC 0 from the 1757–1762 period to present. The comparison was still clouded by factors such as the varied specific locations of the urban AWSs and the early observational instruments, the representativeness of the suburban AWSs data, and the temporal variation of regional climate during the past 20 years.

The relationship between daily T-min and temperature at 8:00 BJT, and between daily T-max and temperature at 15:00 BJT at the four stations are shown in Fig. 4. A highly significant correlation between temperature at 8:00/15:00 BJT and T-min/T-max in the area can be seen,

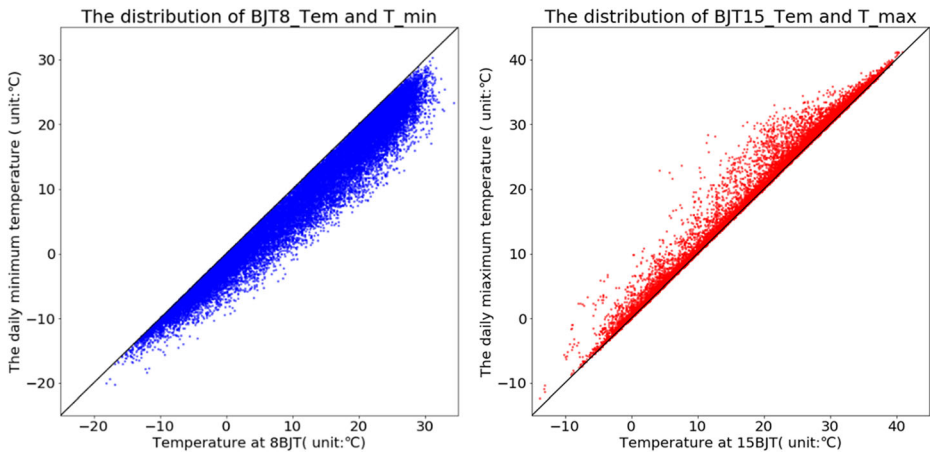


Fig. 4 The relationship between 8:00 BJT temperature and T-min (left), and 15:00 BJT temperature and T-max (right) at the four national stations in Beijing urban area (unit: °C)

which means that the daily T-max and T-min in the mid-eighteenth century can be well interpolated or reconstructed by using these two time observational records.

To improve the precision of the reconstruction method, in addition to the temperature at 8:00 BJT and 15:00 BJT, the temperature difference between 8:00 BJT and 15:00 BJT, the temperature at 8:00 BJT and 15:00 BJT the day before, the temperature difference between 8:00 BJT a day and 8:00 BJT the day before, and so on, were also set as independent variables to fit the daily T-max and T-min at the modern stations. The formulas used are:

$$T_{max} = a_1 T_{8i} + a_2 T_{15i} + a_3 (T_{15i} - T_{15(i-1)}) + a_4 (T_{8i} - T_{8(i-1)}) + a_5 (T_{15(i-1)} - T_{8(i-1)}) \quad (1)$$

$$T_{min} = b_1 T_{8i} + b_2 T_{15i} + b_3 (T_{15i} - T_{15(i-1)}) + b_4 (T_{8i} - T_{8(i-1)}) + b_5 (T_{15(i-1)} - T_{8(i-1)}) \quad (2)$$

where a_1 to a_5 and b_1 to b_5 are coefficients determined from modern observations, T_{8i} is the temperature on day i at 8:00 BJT, $T_{8(i-1)}$ is the temperature on day before i at 8:00 BJT, T_{15i} is the temperature on day i at 15:00 BJT, and $T_{15(i-1)}$ is the temperature on the day before i at 15:00 BJT.

Taking the difference of sunrise times for different seasons into account, the regression formulas for the reconstruction were developed for the 12 months of a year. For every month, the whole data from national stations (2000–2019) was split into two parts, with 70% of the data randomly selected to form the training set and the remaining 30% of the data as the testing set. The training set was fitted by least squares method to estimate parameters, and the testing set was fitted to evaluate the applicability of the parameters.

The observed and fitted daily T-max and T-min were compared in Fig. 5. All regressions pass the 0.01 significance test (Table 1 and Fig. 5). The reconstructed daily T-max matches the observations better, especially during the warm season. After checking the fitted and observed T-min pairs, the worse correspondence came from the higher values of the fitted T-min. The T-min regression formulas could not fit the abnormal minimum values in summer, especially those below 20 °C in June. This might affect the analysis of extreme low temperature events in summer.

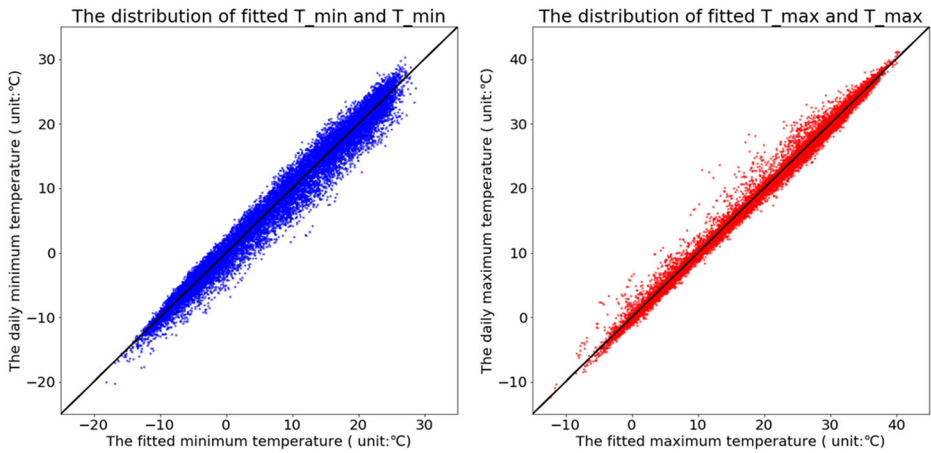


Fig. 5 The correlations of the fitted and observed daily T-min (left) and daily T-max (right) at the four national stations in Beijing urban area (unit: °C)

The daily T-max and T-min from 1757 to 1762 were thus reconstructed. Based on the daily data, the extreme temperature indices were calculated and analyzed, referring to the definitions of extreme temperature indices (Expert Team on Climate Change Detection and Indices, WMO) (Zhang et al. 2011). The extreme temperature events (indices) analyzed in this paper include (Table 2): summer days, tropical nights, warm days, warm nights, frost days, ice days, cool nights, and cool days. The thresholds derived using nonparametric statistics (percentiles), such as 90th and 10th percentiles, were means of the four national stations during the base time period 1981–2010.

3 The extreme temperature in the mid-eighteenth century

3.1 The maximum and minimum temperature

The extreme temperature values in central Beijing during 1757–1762 are listed in Table 3. To avoid the effect of occasional extreme data, the 6-year average values of monthly maximum and minimum values of daily T-max and T-min were also calculated to indicate the difference of extreme temperature values between 1757 and 1762 and 2014–2019 (Figs. 6 and 7). The monthly minimum temperature showed that the extreme minimum temperature (Fig. 8) and mean of extreme minimum temperature (Fig. 6) all happened in January, followed by February and December, during 1757–1762. The cold months, including January, February, and December, shared similar chilly low temperature in the mid-eighteenth century, which was different from those of modern times. The mean February minimum values during 2014–2019 was almost 3.0 °C higher than that in January, but almost no significant extreme minimum

Table 1 The correlation coefficients of fitted and observed temperatures for daily T-max and T-min

Month	1	2	3	4	5	6	7	8	9	10	11	12
T-max	0.97	0.99	0.97	0.95	0.92	0.91	0.94	0.9	0.97	0.97	0.97	0.95
T-min	0.91	0.92	0.91	0.79	0.71	0.65	0.69	0.77	0.84	0.89	0.91	0.9

Table 2 The definitions of extreme temperature indices (Zhang et al. 2011)

ID	Indicator name	Definition	Unit
FD0	Frost day	Annual count when TN (daily minimum) <0 °C	Days
SU25	Summer day	Annual count when TX (daily maximum) >25 °C	Days
ID0	Ice day	Annual count when TX (daily maximum) <0 °C	Days
TR20	Tropical night	Annual count when TN (daily minimum) >20 °C	Days
TXx	Max T-max	Monthly maximum value of daily maximum temp	°C
TNx	Max T-min	Monthly maximum value of daily minimum temp	°C
TXn	Min T-max	Monthly minimum value of daily maximum temp	°C
TNn	Min T-min	Monthly minimum value of daily minimum temp	°C
TN10p	Cool night	Percentage of days when TN < 10th percentile	Days
TX10p	Cool day	Percentage of days when TX < 10th percentile	Days
TN90p	Warm night	Percentage of days when TN > 90th percentile	Days
TX90p	Warm day	Percentage of days when TX > 90th percentile	Days

temperature difference between past and present could be seen for January and December, indicating a more rapid warming of present time occurring in February. The monthly highest daily maximum temperature occurred in June in 1757–1762, and in May in modern times (Fig. 8), rather than in July such as that for the monthly mean maximum temperature (Fig. 7). The mean minimum values of monthly T-max also showed an increase from January to February in present time as compared to the past. This implies that a longer period of extreme cold temperatures during wintertime occurred in 1757–1762 than in present.

The 6-year average value of monthly highest T-min during 1757–1762 is close to or less than that of modern times in most months (Fig. 6). The early year weather exhibited colder extreme values in the cold half of the year, indicating a more obvious increase in the monthly highest daily T-min in present time compared to the mid-eighteenth century. It seems from Figs. 6 and 7 that, 260 years ago, local people had to tolerate a higher extreme temperature but shorter periods of warm extreme climate than modern times in the warm season.

To evaluate the extreme climate during the early six years, 1757–1762, the monthly minimum and maximum temperatures were selected to compare with those of the reference period 1981–2010 and 2014–2019 (Fig. 8). Most monthly minimum temperatures did not exceed the span of those during 1981–2010. In addition, the dispersion of minimum temperature in the early six years was similar to that in 2014–2019. The early period minimum temperatures were lower, especially when compared with 2014–2019. For example, the February mean minimum temperatures in 1757–1762 ranged from -15.5 °C to -11.6 °C. In reference periods, the distribution was from -17.5 °C to -4.9 °C. Except for summer, monthly minimum temperatures in the early years were in the lower part of the reference span. It is also notable that, in the first half of the year, the increase of monthly minimum temperatures with season in 1757–1762 was slower than that in modern times; in the second half of the year,

Table 3 The extreme temperature values and their occurrence dates at the Old North Church of central Beijing during 1757–1762

	Minimum T-min	Minimum T-max	Maximum T-max	Maximum T-min
Temperature	-15.8 °C	-11.2 °C	43.1 °C	27.8 °C
Date	Jan 12, 1762	Jan 30, 1757	June 5, 1760	July 12, 1757

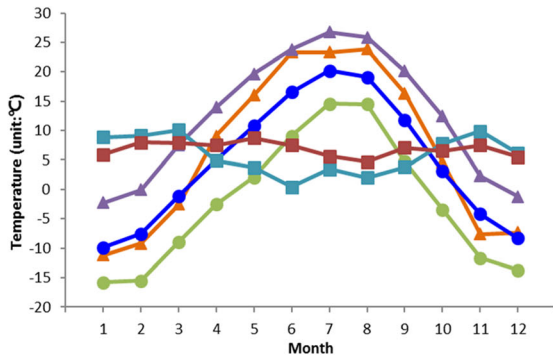


Fig. 6 The average of monthly minimum T-min and T-max during 2014–2019 and 1757–1762, and their differences between the two periods (modern-early years) (unit °C)

however, the decrease of monthly minimum temperature with season in the early years was faster than that in modern times.

The monthly maximum temperatures showed similar intra-annual variation, with the early period temperature increasing more slowly than that in modern times in the first half of the year and decreasing faster in the second half of the year. The distribution of early period maximum temperature in warm season, especially in May, June, July, and August, were similar or even higher than that of the reference period and 2014–2019. In autumn (Sept, Oct, and Nov), the mean monthly maximum temperature in 1757–1762 was much lower than that of the present time, indicating a large increase in maximum temperature today as compared to the past. Not merely for autumn and maximum temperature, but in the transitional seasons of both spring and autumn, the monthly maximum and minimum temperatures in 1757–1762 were obviously lower than those of the 75th percentiles of the reference period and 2014–2019.

It seems that the local people 260 years ago did experience more freezing weather than people do today, especially during the transitional seasons and wintertime. However, the monthly minimum temperatures in 1757–1762 did not exceed the lower extreme values of

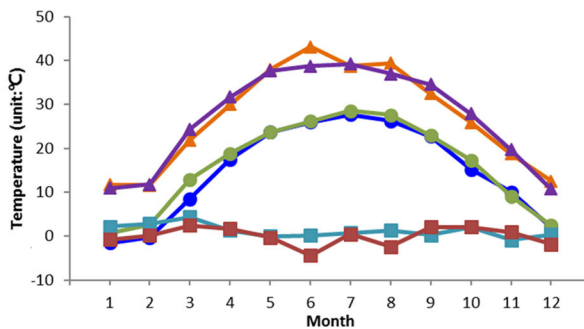


Fig. 7 The average of monthly maximum T-min and T-max during 2014–2019 and 1757–1762, and their differences between the two periods (unit °C)

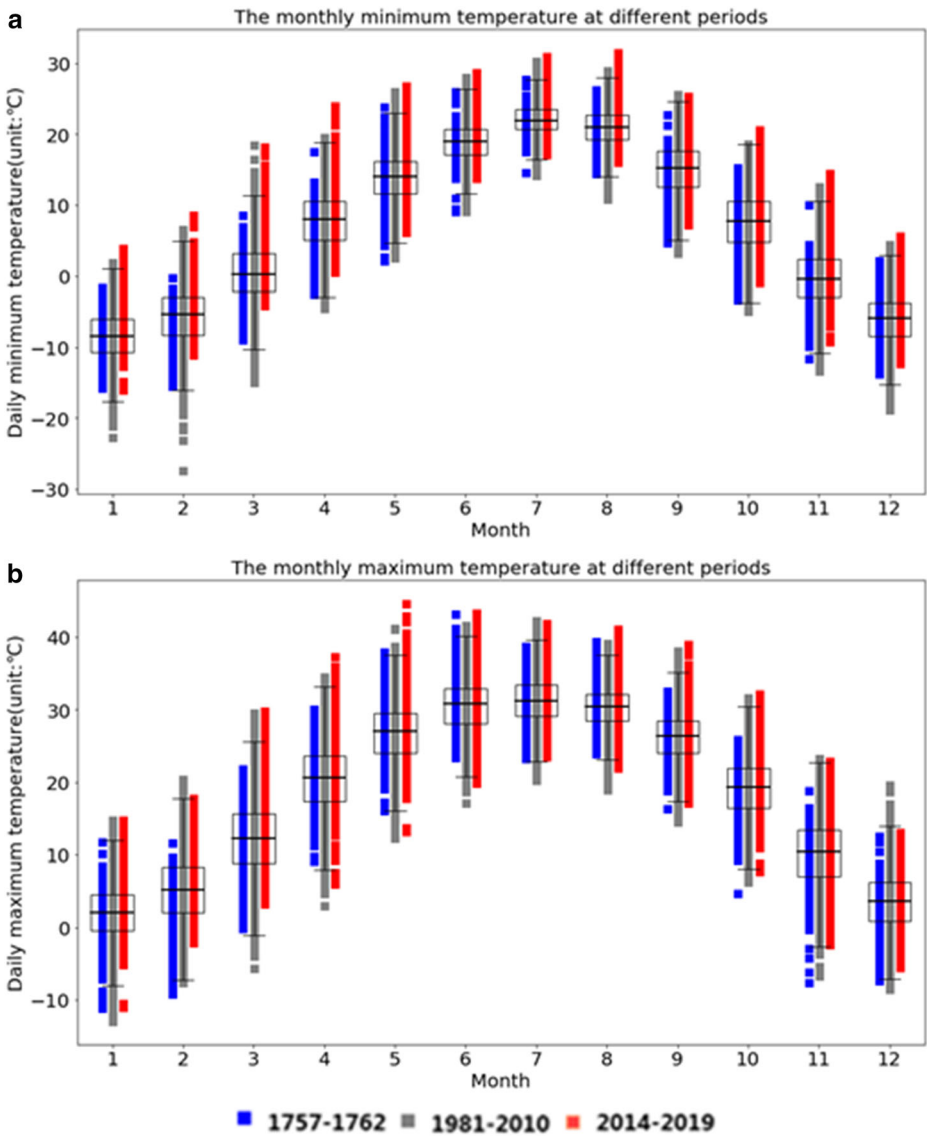


Fig. 8 The monthly minimum temperature (a) and maximum temperature (b) during different periods in the central area of Beijing City. Temperature of 1757–1762 is from the Old North Church and that of 2014–2019 is from the nearby urban AWSs. Boxes indicate the interquartile temperatures (25th and 75th quantiles) with the black horizontal line indicating the median, the whiskers showing the extreme range, and dot indicating the outliers

modern times (reference period of 1981–2010) except for May and June, though the length of time during which lower minimum temperatures occurred was longer than today.

3.2 The warm extreme events

During 1757–1762, the annual summer days (SU25) all exceeded 120 d, and the annual mean SU25 exceeded 130 d, slightly less than the annual mean of 1981–2010, obviously less than

the mean of 2014–2019 (based on the nearby urban AWSs, the same hereinafter). The year 1762 experienced the least SU25 not only during 1757–1762 but also during 1981–2019. There was no significant difference of annual mean SU25 between 1757 and 1762 (132.7 d) and 1981–2019 (138.3 d), but the values of the two periods were obviously lower than in 2014–2019 (155 d) (Fig. 9).

In 1757–1762, the annual TR20 ranged from 36 d to 60 d, with 1762 registering the least TR20 again. All 6 years of the period had a many fewer days of TR20 than those of modern times (1981–2010 and 2014–2019), with the annual mean values of 2014–2019 over 30 d more than those of 1757–1762, indicating a remarkable warming in warm-season nights at present. The TR20 from rural AWS spread between 45d and 80d, nearly 20 d less than that in the central urban area, indicating a significant effect of urbanization on the tempo-spatial pattern of the TR20 in the Beijing region.

The TX90p during 1758–1762 were the most in 1759 (75 d), and the least in 1762 (28 d). During modern times, the largest number of warm days occurred in 2019 (exceeded 85 d), and the smallest number was in 1985 (14 d). The annual mean value of TX90p during the early stage is 63 d, as compared to 37d in 1981–2010 and 76.8 d in 2014–2019. Overall, the number of TX90p witnessed a remarkable drop in the reference period as compared to the mid-eighteenth century in Beijing. In 2014–2019, however, the annual mean number of TX90p had a slight increase related to that of 1758–1762, and a remarkable increase related to that of 1981–2010. The rural areas had a similar number of warm days with the early six years, indicating that the more warm days in the present than in the early years in the central urban area might have been dominantly caused by the urbanization.

The largest annual number of TN90p was 39 d in 1759, and the smallest one was 10 d in 1762, with the annual mean value of 29.6 d in the early stage. All three values were obviously lower than those in modern times, indicating an increase in TN90p with time. However, there

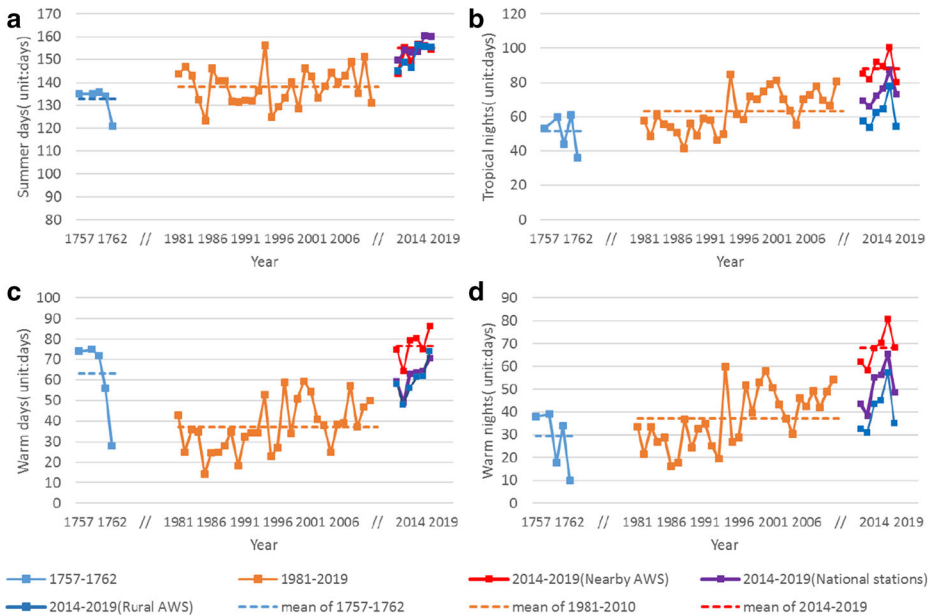


Fig. 9 The annual warm extreme events for periods of 1757–1762, 1981–2010, and 2014–2019 (**a** SU25; **b** TR20; **c** TX90p; **d** TN90p)

was no statistically significant difference of TN90p between 1757 and 1762 and 1981–2010, although the difference between 1756 and 1762 and 2014–2019 was significant at the 0.05 confidence level.

The thresholds of TX90p and TN90p were also calculated by using the data from the national stations during 1981–2010. The temperatures from the national stations were usually lower than those from the urban AWSs. Therefore, the 10th and 90th percentile values obtained were also lower than those in the urban center. The annual mean TX90p and TN90p of the national stations falls in between (the central urban area and the rural areas), consistent with the spatial pattern of the annual mean UHI intensity (Yang et al. 2013).

3.3 The cold extreme events

The annual mean FD0 in 1757–1762 was 126 d, with the most days of 139 in 1759, and the least days of 114 in 1761. By contrast, the largest annual number of FD0 during modern times was 135 d in 1991 during the reference period, and it was below 110 d in 2015 during 2014–2019. The FD0 only witnessed an insignificant decrease for modern times (1981–2010), but a significant drop for 2014–2019.

The annual mean ID0 in the early stage were higher in number than modern times. Two years, 1757 and 1762, had more than 40 days, while the most days in modern times was 39 days in 1985 during 1981–2010, and 23 days in 2018 during 2014–2019, with some years even experiencing less than 10 days of ID0 during 1981–2019.

The annual TX10p was approximately 50 d in the mid-eighteenth century, with the most days of 62 in 1762 and the least days of 39 in 1761. In modern times, the least annual TX10p was 15 d in 2007 and the highest number was 66 d in 1985. The annual mean TX10p significantly decreased from 52 d during 1757–1762 to 38 d during 1981–2010 and 27 d in 2014–2019. The central urban area and the rural areas showed similar annual mean ice days and cool days in the present, suggesting less influence of urbanization on the extreme low T-max.

The TN10p ranged from 28 d in 1761 to 58 d in 1758, with an annual mean of 47.5 d during the early stage. The annual mean TN10p were 36.8 d during 1981–2010 and 25.6 d during 2014–2019. Therefore, the number of TN10p in modern times also experienced a significant decrease as compared to the mid-eighteenth century. The cool nights showed a remarkable difference between the central urban area and the rural areas. The annual mean TN10p was 9 d in the central urban area and 51 d in the rural areas, during 2014–2019. Therefore, the rare TN10p in the city center may be caused by an inappropriate threshold from national stations and the significant decrease in TN10p from the pre-revolution era to present might also have been induced partially by urbanization (Fig. 10).

The 10th percentile values used to calculate TX10p and TN10p were higher at the central urban AWSs, and to less extent at the national stations, than those at the rural AWSs. The frequencies of cool days and cool nights from the urban AWSs were less than those from the rural stations, an indicator of the effect of urbanization or UHI.

4 Discussion

Most of the extreme temperature indices experienced a significant change from the pre-industrial revolution era to modern times, especially in recent years. The extreme temperature

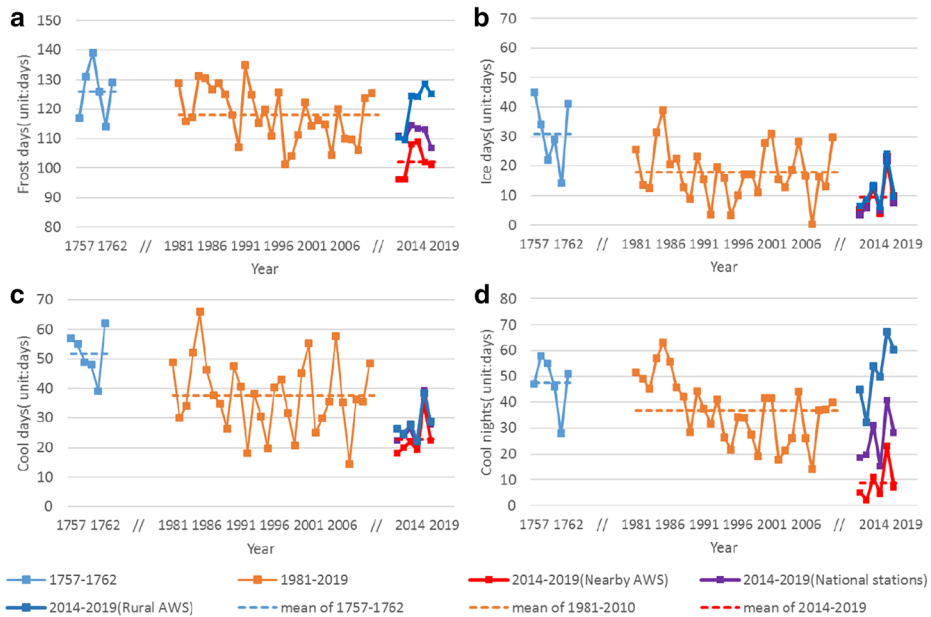


Fig. 10 The annual numbers of cold extreme events for periods of 1757–1762, 1981–2010, and 2014–2019 in Beijing (a FD0; b ID0; c, TX10p; d TN10p)

indices related to the daily maximum temperature generally showed less change compared with those related to the daily minimum temperature. Overall, this pattern of change is consistent with that reported in previous research for North China for the past decades (Zhai and Pan 2003; Li and Yan 2010; Zhou and Ren 2011; Guo et al. 2011).

Due to the varied trends of temperature between different months, different times in a day and different periods (Ren et al. 2015), it is understandable that the changes of extreme temperature indices from 1757 to 1762 to present deviate from those reported for the past decades to a century in the same region. The temperature increase in spring was more than that in the other seasons, while in daily T-min, it was more than that in daily T-max (Table 4). This fact can partly explain the flat difference in some extreme temperature indices between modern times and 1757–1762. The insignificant or small change in SU25 and TR20 would be related to seasonality of temperature trends because the warm-season mean maximum temperature change was always small for most areas of China in the twentieth century (Ren et al. 2005, 2012; Cao et al. 2017). It is also interesting that the period with a similar level of extreme temperature events to that of 1757–

Table 4 The trends of seasonal mean minimum and maximum temperature in different periods at national stations in Beijing urban areas (unit °C/decade)

	1961–2019		1961–1990	
	T-min	T-max	T-min	T-max
Spring	0.57	0.48	0.47	0.11
Summer	0.42	0.31	0.17	−0.25
Autumn	0.40	0.20	0.30	0.23
Winter	0.60	0.31	0.60	0.17

1762 was the first part of 1981–2010, when the global land and China mainland had just begun to warm rapidly.

The distribution of early period and modern daily T-max and T-min could also explain the temporal pattern of the extreme temperature change (Fig. 11). The main difference in daily maximum temperature between 1757 and 1762 and modern times (based on the data of the national stations) was in the distribution of temperature under 0 °C and 25–35 °C. In modern times, the percentage of daily maximum temperature below 0 °C decreased and the percentage of daily maximum temperature ranging from 25 to 35 °C increased. The distribution in other temperature ranges was somehow similar. The percentage of daily T-min below -5 °C decreased, and the percentage of daily T-min ranging from 25 to 30 °C increased. Therefore, the decrease of ice days was more than that of frost days, and the increase of tropic nights (TR20) was more than that of summer days (SU25).

After the rapid warming in recent decades, the temperatures in the past ten or twenty years are obviously higher than in 1757–1762, but in the 1980s and early 1990s, the warming had not increased temperatures to a level significantly different from the 1757–1762 period. Thus, there were some extreme temperature events that showed a similar distribution between 1757 and 1762 and 1981–2000, but a different distribution with 2014–2019.

Except for the effect of global warming, the effect of local environmental change or urbanization played an important role in the difference of the extreme temperature indices between 1757 and 1762 and modern times, and also between different extreme temperature events. In an analysis of a high temperature event in Beijing in 2010, Zhang et al. (2015) found, in the center of Beijing City, close to the location of the early period observations at Old North Church, the annual mean maximum temperature was higher than rural areas by 1.45 °C, and annual mean minimum temperature was higher by 2.93 °C. Zheng et al. (2012), Liu et al. (2013), Ren and Zhou (2014) and Zhang and Ren (2014) also found a more significant difference between urban center and rural areas in minimum temperature than in maximum temperature, and in winter temperature than in spring and summer temperature, in Beijing City. Located in the urban center, the urbanization process inevitably increased the extent and frequency of warm events and decreased the extent and frequency of cold events during recent years.

There might be an uncertainty with the reconstruction of daily maximum and minimum temperatures. In order to further test the feasibility of regression method used to reconstruct T-max and T-min, the daily T-max and T-min in 1757–1762 were fitted based on each of the four reference stations in urban areas (Fig. 12). All of the correlation coefficients between any

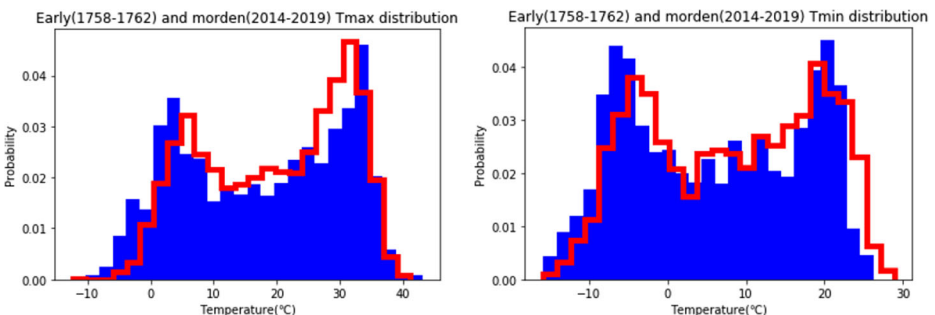


Fig. 11 The distribution of early period (1757–1762, blue bar) and modern daily (2014–2019, red line) T-max (a) and T-min (b) in Beijing. Data of modern times is from the national stations of urban areas

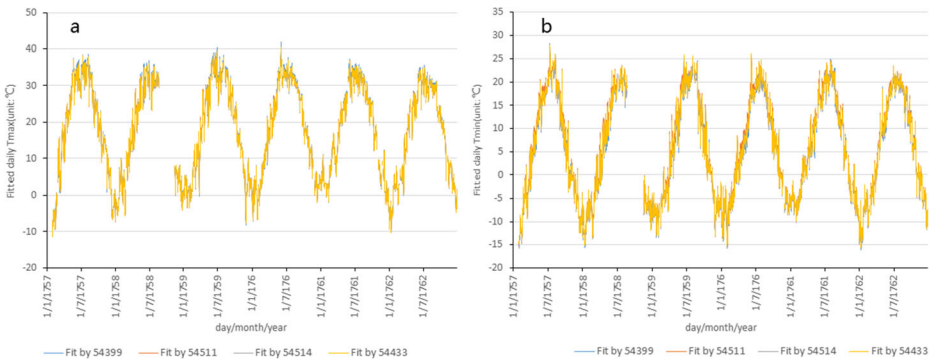


Fig. 12 The 1757–1762 daily T-max (a) and T-min (b) fit based on each of the four central urban stations

two series exceeded 0.99. The difference mainly happened in T-min in June, which exceeded 1.0 °C in some cases. The fitting of testing dataset thus implied an uncertainty in T-min in June, the month of the earliest sunrise. In Beijing, the sun rises around 4:45 BJT in June. After sunrise, temperature increases with the increase of solar radiation, leading to a difficulty for fitting T-min based on hourly mean temperature at 8 BJT. However, the fit was very good for all other months, and the reconstruction of the T-max and T-min would be reliable and applicable for analyzing the early period extreme temperature indices.

Studies with continues instrumental temperature records in the pre-revolution era (mid Qing Dynasty period in China) were rare. There were historical documents including county annals that recorded the unusual weather and climate in the Qing Dynasty. For example, extreme hot and dry weather during the summer in 1743 was recorded in a couple of county annals in North China (Ge 2011). Zhang and Demaree (2004) reported a maximum temperature of 44.0 °C in July based on the rare and incomplete instrumental data. The high temperature records in the historical documents and the early instrumental observations were generally consistent with our results of a higher summer maximum temperature in the earlier six years than today.

By comparing the annual and seasonal mean values of the modern and ancient extreme temperature indices from different areas of Beijing City, we made a tentative evaluation of the urbanization effect on the change in certain indices from the early stage to present. It was clear that the difference of extreme temperature between the past and the present had been caused by both the global and regional climate change, and the local urbanization effect or enhanced UHI intensity around the Old North Church. Further study is needed, however, to differentiate the trends of the extreme temperature indices caused by global and regional warming from those caused by locally anthropogenic urbanization. It is also worth noting that the extreme temperature events of the 1757–1762 period were a little unstable to represent the extreme climate. To better understand the early extreme climate variation and determine the influence of greenhouse gas emissions after the industrial revolution, uncovering more data from 1762 to the mid-twentieth century is also necessary.

5 Conclusions

Based on the observations in Beijing during 1757–1762, and using the relationship of daily T-max and T-min and temperatures at 8 and 15 Beijing time, daily maximum and minimum

temperature during 1757–1762 were reconstructed. Extreme temperature indices were calculated to show the extreme climate 260 years ago and its difference from modern times. The following conclusions could be drawn:

- (1) The extreme minimum T-min ($-15.8\text{ }^{\circ}\text{C}$), minimum T-max ($-11.2\text{ }^{\circ}\text{C}$), maximum T-max ($43.1\text{ }^{\circ}\text{C}$), and maximum T-min ($27.8\text{ }^{\circ}\text{C}$) did not exceed the span of modern extreme temperatures. However, the annual extreme cold period was longer and the probability of cold event occurrences was higher in 1757–1762 than today. The annual hot period was shorter but the daily T-max exceeded $37\text{ }^{\circ}\text{C}$ frequently.
- (2) Between 1757 and 1762 and 2014–2019, there were significant differences in warm extreme events frequencies. During 1757–1762, the annual summer days never exceeded 140 days, while during 2014–2019, the least summer days were more than 140 days. The tropical nights also showed a remarkable difference, but the differences in warm nights were relatively moderate. All of the cold extreme events frequencies showed a significant decrease in 2014–2019 compared with in 1757–1762.
- (3) The decrease of cold events from 260 years ago to today was more obvious than the increase of warm events, and the change of extreme temperature indices related to minimum temperature was more significant than that related to maximum temperature. The T-min showed a more rapid increase trend than T-max. Temperature in early spring and winter showed a more rapid increase trend than in summer.
- (4) The temporal pattern of extreme temperature change at the ancient observational site was consistent with global and regional warming, as well as the local urbanization effect. However, the possible causes of the extreme temperature difference between the past and present need to be further investigated.

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