

The 1757–62 Temperature Observed in Beijing

Yuyu Ren, Guoyu Ren, Rob Allan, Jiao Li, Guowei Yang, and Panfeng Zhang

ABSTRACT: Instrumental data from the pre–Industrial Revolution period are important to understand climate change. In this paper, the observations made by the French missionary J. Amiot in present-day central Beijing during 1757–62 were processed and analyzed. The observations represent the earliest continuous dataset of meteorological records found in China that have been digitized recently. Comparisons between the Amiot annual temperature range and extreme values with modern observations showed that the observations were read at approximately 0800 and 1500 local solar time (LST) in a well-ventilated outdoor site. The daily maximum, minimum, and mean temperatures (T-max, T-min, and T-mean, respectively) during 1757–62 were determined by examining the relationship between temperature at 0800 and 1500 LST and T-max, T-min, and T-mean in modern reference series. Nearly 260 years ago, Beijing's climate was typical of an inland temperate monsoon zone with annual T-mean, annual mean T-max, and annual mean T-min being 11.5°, 17.8°, and 6.1°C, respectively; further, the temperatures did not vary considerably from the 1951–1980 temperatures, but differed evidently compared to relatively recent decades (1981–2020). The difference was larger than the magnitudes of global and regional temperature changes. Thus, climate warming since the pre-Industrial Revolution period in the urban areas of Beijing has dominantly occurred over the last four decades. Uncertainties related to the thermometer and observational conditions 260 years ago and the interpolation method used have also been discussed in this paper.

KEYWORDS: Asia; Climate change; Climate records; Climatology; Temperature

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Corresponding author: G. Ren, guoyoo@cma.cn

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ong-term continuous observations of surface air temperature (SAT) are important to understand recent and historical climate change events. Moreover, they could assist in understanding the relative importance of natural and anthropogenic drivers of rapid temperature increases in recent decades, capability of current models to simulate past climate variability and changes, and what the observed temperature was during the pre–Industrial Revolution period, which has been regarded as a reference (under the Paris Agreement) to assess the possible period of the increase in global surface temperature by 2.0°/1.5°C (Hulme 2016; Schurer et al. 2017). Additionally, early temperature and air pressure observations are also necessary for historical reanalysis, such as the Twentieth Century Reanalysis (Compo et al. 2011; Camuffo and Jones 2002; Brönnimann et al. 2019).

Relatively reliable SAT data series dating back to 1850 or even earlier have been reconstructed in some European countries, Australia and New Zealand, South America, North America, and East Asia. Based on these data, analysis of long-term temperature indices and their variabilities for various sites and small-scale regions have improved our knowledge of climate variability (e.g., Jones 2001; Cornes 2010; Camuffo and Bertolin 2012; Lorrey and Chappell 2015; Hestmark and Nordli 2016; Zaiki et al. 2006; Demarée et al. 2013; Können et al. 2003; Matulla et al. 2008; Pfister et al. 2019). Such series can also be employed as a reference series to assess other temperature series and reconstruct further reliable long-term series on a larger spatial scale.

However, climate data, including temperature data, are insufficient for assessing climate regimes in the early periods, especially those before the 1850s, for many countries and regions (Brönnimann et al. 2019). For example, SAT data for Africa, inland regions of China, and South America are rarely available for periods before the 1950s (Domínguez-Castro et al. 2017; Sun et al. 2017), let alone for earlier years. Thus, although some studies have attempted to bridge this gap, this lack of data hinders our understanding of a complete early-year climate change pattern and efforts to reconstruct historical global atmospheric circulation fields (e.g., Domínguez-Castro et al. 2017; Williamson et al. 2018).

The Atmospheric Circulation Reconstructions over the Earth initiative aims to facilitate the recovery, imaging/scanning, and digitization of historical instrumental climate observations to underpin climate reanalysis over the last 200–250 years. Some records in the recent 200 years have been extracted and digitized that has greatly facilitated the detection and historical reanalysis of early-year extreme climate change (Brönnimann et al. 2019; Domínguez-Castro et al. 2017; Compo et al. 2011).

Many studies have examined the long-term SAT changes over the last 100 years across China using monthly data (Wang et al. 1998; Tang and Ren 2005; Cao et al. 2017). These studies can help in understanding the temperature changes in China after 1900. Additionally, few daily 100-yr SAT data series exist that were constructed to investigate the 100-yr extreme temperature changes in cities, including Tianjin, Shanghai, and Yingkou (Cui et al. 2009; Guo et al. 2011; Si et al. 2021; Xue et al. 2021). These investigations are valuable to detect and attribute extreme climate changes in local areas over the last six decades or more. Furthermore, the extraction, digitization, and analysis of pre-1950 climate records of mainland China initiated in 2012 under the framework of the U.K. Newton Fund's Climate Science for Service Partnership for China (www.metoffice.gov.uk/research/approach/collaboration/ newton/climate-science-for-service-partnership-china) and the support of the China Meteorological Administration (CMA) and China University of Geosciences (Wuhan) (Williamson et al. 2018). Presently, this research is proving to be advantageous, with some of the digitized data being used to analyze the early year mean and extreme temperature changes in various cities across China (Guo et al. 2011; Yu et al. 2020; Ren et al. 2021; Xue et al. 2021).

In this study, research related to the earliest continuous SAT records, which have recently been digitized, were reported. The observations were made in Beijing by the French missionary, Jean Joseph Marie Amiot, during 1757–62 (Messier 1774), which probably represented the earliest instrumental observations of longer than one year that have been recorded in the East Asia. In the sixteenth century, several Catholic missionaries came to China to spread Catholicism, astronomy, calendars, and mathematics and some of them charged the central calendar department of the Qing Dynasty (Udías 1994). The observations were sent back to their funding agencies and stored in science institutes or libraries (Domínguez-Castro et al. 2017). For example, from July 1743 to March 1746, another France missionary Antoine Gaubil conducted weather observations in Beijing, and approximately 250 days of SAT records were stored (Zhang and Demaree 2004). These represented the earliest observations by the West Jesuits in Beijing. However, the earliest continuous observations lasting more than one year are those recorded by Amiot.

Amiot preached in the Old North Church, a Catholic church, which used to be the Bishop's Cathedral, in the then suburb of Beijing of the Qing Dynasty, during the reign of the Qianlong emperor (Fig. 1). Due to the extension back to the mid-eighteenth century (pre–Industrial Revolution) and their good continuity, the SAT dataset is highly valuable to understand the background climate status and variability in North China.

Observational data have been used to analyze the climatology of Beijing and compare it with that of other regions worldwide (Mahlmann 1843). As understanding the global spatial climate differences was important during the pre-twentieth century, early data, such as Amiot observations, were highly valuable. However, processing (quality control) of observational data during the mid-nineteenth century was not advanced, and errors in daily and monthly mean temperatures (T-mean) were sometimes significant. More importantly, the significance of the data in addressing modern climate issues, including preindustrial climate characteristics, in terms of defining suitable climatological base periods and characteristics of natural climatic variability during the relatively warm stage of the Little Ice Age, has not been investigated.

Thus, this study aims to bridge these research gaps. Our previous study provides comprehensive descriptions of the Amiot observations, data processing and quality control, and extreme temperature variations during the mid-eighteenth century (Ren et al. 2021). Other interesting climate information, including surface air pressure, rainy days, wind direction, cold waves, and dust storms, in the Amiot observations can provide further understanding of the local climate characteristics and variability during that period. However, due to space constraints, these aspects will be analyzed in future studies.

The remaining paper is organized as follows: The second section describes the Amiot observations and records, and the methods used to analyze them. The third section describes the investigations of temperature climatology during 1757–62 and compares the results with

those of different times. Finally, the study has been summarized and future prospects have been explained in the fourth section.

Materials and methods Amiot observations in Beijing.

From January 1757 to December 1762, Amiot carried out climate observations in a church called Laobeitang Church (Old North Church) located west of the Forbidden City, central Beijing. Observations were recorded twice a day in the morning and afternoon local time (BJT). He measured SAT and atmospheric pressure, and recorded weather phenomena of wind direction, rains, strong winds, cold surges, and snowfall. The observations were collected and edited for printing the booklet "Observations Meteorologiques Faites A Pekin" (Messier 1774) (Fig. 1). Its photocopy is stored in the National Library of France and is freely accessible to the public (https://gallica.bnf.fr/ark:/12148/ bpt6k6395701s).



Fig. 1. (top left) Jean Joseph Marie Amiot, (top right) Old North Church (now Xishiku Church), and the (bottom left) title page and (bottom right) sample record sheet of the archive.

The church, where observations were conducted, was originally located in Canchikou, on the west bank of the Zhonghai Lake, adjacent to the Forbidden City. This site is presently located downtown of Beijing City. Generally, the areas surrounded by the Fourth or Third Ring Road comprise central Beijing. Presently, the observational site is now within the Second Ring Road, and thus, it is located in the center of the downtown area. The church was built in 1683 and named as "Savior Hall," but was also called "North Church" by the residents. The observations were probably made in the structure next to Savior Hall, or in the bell tower (13.0 m tall) in the Savior Hall. Figure 2 shows the relative location of the church in central Beijing.

The original observational records were of high quality and were conducted at precise time schedules and using the then most advanced instruments. The thermometer used by Amiot was calibrated against Reaumur's high-quality thermometer, and the subsequent data were comparable with those recorded in France at that time. During the six observational years, only the daily records of the start of January 1757 and from September to November 1758 are missing, accounting for approximately 4.1% of the total records. Moreover, quality control tests of the temperature data revealed extremely less outliers and errors (Ren et al. 2021).

The Réaumur scale (°R), used by Amiot, was converted to the Celsius scale (°C), which is commonly used presently, according to 1.0° C = 0.8° R, or by multiplying the °R value by 1.25.

Verification and processing of the observational data. Comparison of the SAT recorded by Amiot with the modern SAT data affirmed that the microenvironment was represented

appropriately around the Amiot's observational site and instrumental layout (Ren et al. 2021). The thermometers must have been placed outdoors, and observation must have been made in the afternoon around 0700 UTC (1500 BJT), which is close to the present occurrence time of maximum temperature (T-max) in Beijing. The comparison also confirmed that the morning temperature was observed by Amiot around 0800 BJT, which is on average slightly higher than the daily minimum temperature (T-min) registered generally at dawn.



Fig. 2. Location of Amiot observations (red cross), reference station (ID: 54511; blue cross), city boundary in 1750 (red hoop, approximately corresponding to the present Second Ring Road), and Fourth–Sixth Ring Road (blue hoop).

The digitized data were subjected to quality control to detect and correct any errors. Accordingly, value repetition, outlier, and time consistency tests were performed, while the cross-consistency test for different variables was employed to separate the extreme events and errors due to the absence of a reference series. However, the data series was not homogenized and a reference data series to check breakpoints was absent. Further, as there were no records of station relocation and instrumentation changing during the six years, it could be assumed that the temporal homogeneity of the data was high.

Maximum and minimum temperatures. In Beijing, the average temperature at 1500 BJT was extremely close to the current daily T-max, and the temperature at 0800 BJT was approximately close to the daily T-min. However, they did not exactly represent T-max and T-min, and thus, the exact temperatures should be determined to calculate other temperature indicators, such as daily T-mean and extreme temperature indices. This was achieved by establishing the relationship of the 0800 and 1500 BJT temperatures with T-max, T-min, and T-mean using modern hourly T-mean data for each month around Beijing. Thus, the daily T-mean could be calculated. However, it differed marginally from the calculated temperature acquired using the same time-interval hourly data, with the former being higher than the latter (Liu et al. 2005; Liu et al. 2019). However, the T-max–T-min averaging method is consistently used internationally, and the daily and monthly T-mean values acquired through this method are comparable with those observed in other studies.

Modern observational data. The climatological features in the mid-eighteenth century were compared with the modern climatological features. The modern daily observational data, which were acquired from the National Meteorological Information Center, CMA, and quality controlled (Liu and Ren 2005; Ren et al. 2018), were used for analyzing the temporal changes in temperature. The locations of the reference stations used in this study and the Beijing Observatory are shown in Fig. 2.

Statistical methods. The monthly T-mean is the average daily temperature of all days of a month, and the annual T-mean is the average of monthly T-mean of all months of a year. The observations were conducted in winter (December of the previous year, January, and

February), spring (March, April, and May), summer (June, July, and August), and autumn (September, October, and November).

Results

Temperature of old Beijing.

DAILY TEMPERATURE OF OLD BEUING. Time series of the daily temperature in 1757–62 and the running T-mean with an 11-day interval are plotted in Fig. 3. A relatively long cold season and a hot season of almost equal lengths were observed each year, between which autumn and spring were observed. The daily T-mean varied between –10.0° and 30.0°C and showed large annual differences seasonally. Each cold season (daily T-mean \leq 0°C) and warm season (daily T-mean \geq 22.0°C) lasted for approximately 90 days. Further, evident temperature differences were observed in both seasons during 1757–1962. The temperatures in the hot seasons of 1757 and 1759 were higher than in the hot seasons of 1758 or 1762, while the cold seasons of 1759 (December 1758–February 1759) and 1761 (December 1760–February 1761) were less harsh than those of other years.

The daily T-max exceeded 30.0°C from mid- to late May, while it was mostly 35.0°C in June and July. In 1759 and 1760, high temperatures of >40.0°C were recorded in June. The unexpectedly high temperatures were consistent with previous disaster records and those observed in previous climate studies conducted during the Qing Dynasty (Ge 2011; Zhang and Demaree 2004). In winter, the T-max fluctuated around 0°C and 8% days per year on average fell below 0°C, and the overall T-max range varied between –10.0° and 45.0°C.

In 1757–62, the daily T-min fell below 0°C in mid-November and below –5°C in late November. In January, T-min often fell below –10°C. In mid-March, T-min was increased further to above freezing temperature. During June–August, the daily T-min was 20.0°–30.0°C. In winter, T-min varied between –15.0° and 0°C.

The annual Amiot temperature range frequently exceeded 50.0°C, which was consistent with that of modern Beijing climate, with annual temperature ranges between 45.0° and 65.0°C. Further, during 1951–2020, the temperature exceeded 50.0°C. Large temperature fluctuations during the day and annually were notable characteristics of Beijing climate.

To analyze the annual variability in temperature 260 years ago, we compared the daily T-mean, T-max, T-min, daily temperature range (DTR), and the average values for 1757–62, with their present day thresholds (upper threshold: daily T-mean of 1951–2020 plus 3 times the standard deviation; lower threshold: daily T-mean minus 3 times the standard deviation) (Fig. 4). We found that 260 years ago, the temperatures in the first half of the year showed



Fig. 3. Daily mean, maximum, and minimum temperature series (T-mean, T-min, and T-max, respectively) at Old North Church of Beijing in 1757–62.

a more dispersed distribution than those in the second half, with the T-max being more dispersed than the T-min. Temperatures increased slightly from January to February, and then increased rapidly from March to June. However, the temperature differences in June, July, and August were marginal. During August–November, temperatures decreased rapidly. The temperatures in December were slightly higher than those in January and the T-max increased more rapidly than T-min in spring.

Due to the different intraseasonal warming and cooling rates, DTR in spring and autumn were higher than in the other two seasons. The average monthly mean DTR in May during 1757–62 exceeded 15.0°C. December exhibited the lowest DTR (<9.0°C). High DTR in spring and rapid transition from winter to summer were characteristic of the modern Beijing climate. Compared with modern times, most temperatures were located in the range of the modern temperature thresholds. Among them, T-max and T-mean in winter, especially in February, were slightly less, with the daily T-max in 1757–62 being much closer to the lower threshold. The



Fig. 4. Average and daily T-max, T-mean, T-min, and DTR series at Old North Church of Beijing in 1757–62. The upper and lower thresholds were derived from the daily means of 1951–2020 \pm 3 times the standard deviation, respectively.

T-min in April and May during 1757–62 mainly included the lower values of the modern temperature threshold. Additionally, the DTR showed some differences. In spring, as T-max and T-min increased slowly and rapidly, respectively, the DTR during 1757–62 was higher than that in modern times. Compared with modern times, the mean T-max was lower in January and December and higher in June, July, and August of 1757–62, thus, consequently, resulted in a rapid increase in T-max from winter to summer and a decrease from summer to winter. Moreover, the temperature during the daytime in 1757–62 was more sensitive to the seasonal variations of solar radiation than in modern times.

During 1757–62, the ranges of monthly T-mean, T-max, and T-min were from –10.0° to 30.0°, from –5.0° to 40.0°, and from –10.0° to 25.0°C, respectively, and the DTR was 5.8°–18.2°C.

Furthermore, the climate of Beijing 260 years ago represented a typical temperate climate characterized by cold winters, hot summers, large temperature differences between winter and summer, and four distinct seasons. The mean spring, summer, autumn, and winter temperatures in 1757–62 were 12.5°, 26.2°, 11.4°, and –4.0°C, respectively. Further, in spring,

summer, autumn, and winter, the mean seasonal T-max was 19.5°, 32.4°, 17.4°, and 1.7°C, respectively, while the mean seasonal T-min was 5.4°, 20.0°, 6.0°, and -7.4°C, respectively. In summer, T-max exceeded 30.0°C and the T-mean was >25.0°C. Moreover, in winter, T-min was <-5.0°C and the T-mean was also well below the freezing temperature. The highest temperature range between the summer T-max and winter T-min was <40.0°C, and the T-max in spring was higher than that in autumn, while the T-min in spring was slightly lower



Fig. 5. Seasonal maximum and minimum mean temperatures, and temperature range at Old North Church of Beijing in 1757–62. Boxes indicate the interquartile temperatures (25th and 75th quantiles), with the black horizontal line indicating the median and the whiskers showing the extreme range at the reference station during 1951–2020.

than that in autumn. Owing to rapid global warming in the recent 30 years, the seasonal temperatures in 1757–62 were at the lower–middle level of the 1951–2020 values (Fig. 5).

Comparison with the temperature of other periods. In China, several historical documents, such as local governmental gazettes and archives, and private diaries of researchers, contain climate information. Based on these documents, many climate series of several hundred to 2,000 years have been reconstructed (Zhang and Gong 1980; Zhang and Thomas 1989; Wang and Wang 1990; Wang 1990; Wang et al. 1998; Hao et al. 2018, 2020). To understand the characteristics of the temperature observations during 1757–62 relative to the recent several hundred years, the reconstructed annual T-mean anomaly in east China during the last 500 years (Wang 1990), observed annual T-mean in 1841 in Beijing (Mahlmann 1843), and annual T-mean collected from reference stations in 1951–2020 [representing the climate before and during rapid global (regional) warming] were compared with the temperature series constructed using Amiot records (Fig. 6). Wang (1990) reconstructed temperature series using historical documents from five cities (Beijing, Taiyuan, Jinan, Zhengzhou, and Xuzhou). This temperature series was consistent with other series in nearby areas and is a good representation of Beijing's temperature regime (Wang et al. 1998; Ge et al. 2007).

On using the 1757–62 T-mean to represent the 1750–69 T-mean, we found that the difference between the observed 6-yr T-mean and the 20-yr proxy T-mean anomaly was almost equal to that between the modern 50-yr (1950–99) T-mean and the corresponding proxy T-mean anomaly (Fig. 6). Thus, the reliability and comparability of the two (instrumental and proxy) temperatures were verified.

The mean anomaly values of Wang's series during 1380–1880 and 1750–69 were 0.0° and 0.1°C, respectively. The instrument-based T-mean during 1841 was 10.6°C, which was within the T-mean range of the 1757–62 period. Compared to the 1380–1880 temperatures, the 1757–62 temperatures were slightly higher, but neither extremely cold nor extremely hot. This was consistent with the findings of Yan (2014) and Hao et al. (2020). Thus, instead of proxy data, the instrumental temperature during 1757–62 was a good representation of the temperature in Beijing 260 years ago and could assist in understanding the climate more comprehensively.

In comparison with modern times, the instrumental period was divided into three stages: 1951–80, 1981–2020, and 2001–20, of which 1951–80 represents a period of transition from



Fig. 6. Reconstructed annual T-mean anomaly in east China during 1380s–1990s from historical documents (Wang 1990) and T-mean in 1757–62 from Amiot records, 1841 from Mahlmann (1843), and 1951–2020 from reference stations. The left and right ordinates were adjusted to indicate the same temperature range from –10° to 15°C for annual temperature anomaly reconstructed using the historical documents, and from 0° to 25°C for annual mean temperature from observations in different periods.

midcentury slower rates to late-century acceleration, 1981–2020 represents rapid regional warming in China (Ding and Ren 2007), and the last two decades represent a regional warming slowdown in northern and eastern China and in most of the mid- to low latitudes of the Asian continent (Sun et al. 2017, 2019).

The temperatures and their differences across different periods (modern times minus early times) are shown in Table 1. Temperatures between 1757–62 and 1951–80 did not majorly differ. The annual T-mean increased by 1.9°C from 1757–62 to 2000–20 and by 2.1°C from 1757–62 to 2015–20, which was almost of the same magnitude as the recent temperature increase in the 1950s.

Rather than using single annual temperatures, the annual T-mean distributions were compared. The T-max variation range was 16.4°–18.9°C in 1757–62 and 15.9°–18.9°C in 1951–80. Moreover, T-max variations in 1757–62 were slightly higher than those in 1951–80, which represented the period of transition from midcentury slower rates to late-century acceleration. The annual T-mean variation range was 10.3°–12.5°C in 1757–62

| Temperature | Annual T-mean | Annual T-max | Annual T-min | Winter T-mean | Winter T-max | Winter T-min |
|--------------------------------|------------------|-----------------|-----------------|------------------|-----------------|-----------------|
| 1757–62 | 11.5 | 17.8 | 6.1 | -3.4 | 2.5 | -7.0 |
| 1951–80 | 11.4 | 17.5 | 6.1 | -3.2 | 2.7 | -8.2 |
| 1981–2020 | 13.0 | 18.4 | 8.1 | -1.2 | 3.9 | -5.6 |
| 2001–20 | 13.4 | 18.7 | 8.5 | -1.0 | 4.0 | -5.4 |
| 2015–20 | 13.6 | 19.2 | 8.7 | -0.6 | 4.6 | -5.4 |
| Change from 1757–62 to 2000–20 | 1.9 | 0.9 | 2.4 | 2.4 | 1.5 | 2.6 |
| Change from 1757–62 to 2015–20 | 2.1 | 1.4 | 2.6 | 2.8 | 2.1 | 2.6 |

| Table 1. | Temp | eratures | in | different | periods | and | their | differences | : (| °C |). |
|----------|------|----------|----|-----------|---------|-----|-------|-------------|-----|----|----|
|----------|------|----------|----|-----------|---------|-----|-------|-------------|-----|----|----|

and 10.5°–12.8°C in 1951–80, while the annual T-min variation range was 4.8°–6.9°C in 1757–62 and 5.3°–7.2°C in 1951–80. The range of temperatures in 1991–2020 increased integrally, with the range of T-max, T-mean, and T-min being 17.5°–19.6°, 12.5°–14.2°, and 7.6°–9.3°C, respectively. Moreover, the minimum T-min (7.6°C) in 1991–2020 was higher than the maximum T-min (6.9°C) in 1757–1762.

The temperatures 260 years ago also did not differ considerably in comparison to the temperatures in 1951–80, but they differed evidently from the temperatures after the second half of the 1980s that witnessed rapid temperature increase caused by global and regional warming. Further, the increase in T-min of modern times was more rapid than that in T-mean and T-max.

In Beijing, winter witnessed rapid warming. To understand the long-term temperature changes in winter, the reconstructed winter temperature in east China during 1470–1970 acquired using historical documents (Wang and Wang 1990) was compared with the Amiot records and observations (Fig. 7).

Temperature changed evidently in three turning points, namely, the 1650s, 1760s, and 1870s, in the winter anomaly series. The winter temperature in east China decreased from the 1470s to the 1660s, increased from the 1650s to the 1760s, decreased from the 1760s to the 1870s, and then increased again after the 1870s. Thus, the Amiot observations recorded relatively higher winter temperatures. However, the winter temperatures in 1757–62 were similar to those in 1951–80 and the T-min in 1757–62 were further higher than those in 1951–80. However, after the 1960s, the winter temperatures started increasing rapidly. The winter temperature after the 1970s was higher than that during 1757–62. The differences in winter temperatures between 2001–20 and 1757–62 were higher than those of the annual temperatures.

Therefore, the temperatures before the Industrial Revolution were similar to those in the 1960s and 1970s. The temperature increase in central Beijing after the Industrial Revolution, or in the last 260 years, was mainly caused by the temperature increase in the recent four decades. In other words, the local climate warming since the pre–Industrial Revolution period in the urban areas of Beijing occurred mainly after 1980s. The decadal to multidecadal warming as seen in the pre-1970s period, including that from the late



Fig. 7. Reconstructed winter T-mean anomaly in east China during 1470s–1970s acquired from historical documents (Wang and Wang 1990) and winter T-mean in 1757–62 acquired from Amiot records and 1951–2020 from the reference station.

seventeenth century to the early eighteenth century and from the late nineteenth century to the early twentieth century, exhibited no significant difference in temperature increase rates and magnitudes.

Discussion and conclusions

The subdaily meteorological records, observed by the French missionary Amiot in Beijing during 1757–62 and stored in the National Library of France, were digitized and analyzed. Temperature, pressure, wind direction, and other meteorological variables were analyzed. However, in this study, we analyzed only the temperature and compared temperature difference between 1757–62 and 1951–2020.

As exact metadata and reference records for the Amiot data are lacking, modern observations were used to determine the necessary meteorological metrics of the Amiot observations. After conversion to modern units and quality control, relationships between T-max, T-min, T-mean, and the temperature at 0800 and 1500 BJT were determined through correlations with the data acquired from modern reference stations; consequently, the daily T-max, T-min, and T-mean in 1757–62 were obtained.

The climate of Beijing 260 years ago was a typical temperate monsoon climate characterized by cold winter, hot summer, large DTR, large temperature differences between winter and summer and among the four distinctive seasons. The mean spring, summer, autumn, and winter temperatures in 1757–62 were 12.5°, 26.2°, 11.4°, and –4.0°C, respectively. The annual T-mean was 11.5°C, and the annual mean T-max and T-min were 17.8° and 6.1°C, respectively. The daily T-mean ranged between –10.0° and 30.0°C, T-max in summer often exceeded 35.0°C, and occasionally exceeded 40.0°C, and the daily T-min fell below –15.0°C. Moreover, the monthly mean DTR exceeded 15.0°C in spring.

Compared with present Beijing temperatures, the temperatures 260 years ago did not substantially differ from those of 1951–80 but differed evidently from the temperatures after the mid-1980s. The annual T-mean, T-max, and T-min were 2.1°C (1.9°C), 1.4°C (0.9°C), and 2.6°C (2.4°C), respectively, higher in the recent 6 years (recent 20 years) than those observed 260 years ago. The temperature difference in winter was relatively larger. These temperature increases were significantly larger than the magnitudes of global and regional changes. The large differences between the past and present temperature could be attributed to the urbanization effect and global and regional warming.

The 1757–62 observations in Beijing were made in a relatively warm period of the Little Ice Age; therefore, the mean and extreme temperatures may be slightly higher than those in other periods of relatively cold centuries (Zhang and Demaree 2004). The reconstruction of temperature anomaly in east China during the last 500 years using historical documents showed that the annual T-mean during 1757–62 was slightly higher than that during the 1380s–1880s. However, the overall temperature 260 years ago could still well represent the pre–Industrial Revolution period due to the relatively small temperature variations from 1500 to 1800 (Wang 1990) and, thus, provides a reference to understand modern and projected climate warming. Moreover, these temperatures provide a perspective of the climate in Beijing during 1757–62. However, one drawback is the separation of the global (and probably regional) and local anthropogenic warming at the old observational site of the present-day central Beijing. The local anthropogenic warming would have been dominantly caused by urbanization in the modern time (Ren et al. 2007).

The accuracy of the instrumental measurements 260 years ago, observational environment, location of the instruments, operational criterion (Chang 2001; Winkler 2009; Pappert et al. 2021; Camuffo et al. 2021), and interpolation of daily T-max and T-min with limited observations might have caused uncertainties in our study. A problem with early-era thermometer accuracy is positive bias, probably up to an annual mean of +0.6°C, due to the possible

influence of the glass deformation (contraction) during the first years of its application (Chang 2001; Winkler 2009). However, it is unclear whether the thermometer used by Amiot was first used in 1757. This bias could not be assessed in the present study; notably, as the thermometer was manufactured in Europe, it was potentially not used for the first time in Beijing. Another issue that may have hindered comparability between the early and modern observations is the location of the thermometer. If it was located in the bell tower of the main building of the church, ventilation and shielding from solar radiation was possible, but if it was located at a relative altitude of 13.0 m, a negative annual mean bias of approximately –0.1°C would have been caused. However, this bias is small, and it offsets the possible positive bias caused by the glass contraction of the thermometer to a certain extent.

Moreover, the possible location of the thermometer was a north-facing wall outside the observatory or the main building of the church, if it was not located in the bell tower. However, this possibility could not be verified presently as the records in early morning (0430–0600 BJT) and late afternoon (1800–1930 BJT), when the solar radiation could project onto the wall during early summer, are lacking. The original observations and the reconstructed T-max and T-min could not provide any information on the possible influence of direct solar radiation in early summer (around summer solstice) on temperature measurements, although abnormal shifts were not observed. Thus, these potential sources of uncertainties can only be evaluated when further information is available.

Overall, the uncertainty of the Amiot observations was small; thus, the early-period temperature records could serve as a reference data series for understanding the previous climate regime, against which the observed and projected local SAT increases relative to the pre–Industrial Revolution period could be assessed. Additionally, the comparison of the annual T-mean during 1757–62 and the present could provide a perspective on the long-term SAT changes in central Beijing City. The comparison showed that the local climate warming since the pre–Industrial Revolution period in the urban areas of Beijing occurred primarily over the last four decades, and the SAT may have changed marginally in terms of its long-term trend during the remaining 220 years. These finding presented in this paper would thus assist in further detecting and attributing the past climate warming and in projecting the future climate trend over Beijing as well as North China.

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Data availability statement. All meteorological data used during this study are openly available from the Guoyu Ren Project website at www.rengy.cn and the UCAR data website at https://rda.ucar.edu/.

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